NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

DISTRIBUTED AGENT-BASED NETWORKS IN SUPPORT OF ADVANCED MARINE CORPS COMMAND AND CONTROL CONCEPT

by

Joseph W. M. Rivera

September 2012

Thesis Advisor:	Alex Bordetsky
Second Reader:	John Looney

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2012	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE Distributed Agent-Based Networks In Support of Advanced Marine Corps Command And Control Concept

5. FUNDING NUMBERS

6. AUTHOR(S) Joseph W. M. Rivera

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ___N/A____.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE
A

13. ABSTRACT (maximum 200 words)

The capabilities that Mobile Ad Hoc Networking (MANET) technologies can provide to the Marine Corps are just fully coming into view. These new capabilities represent a much more apparent symbiotic relationship between maneuver at the tactical level and the capabilities of a network that supports that maneuver. However, in order to properly leverage these capabilities, a paradigm shift in what networks are and how they are managed must take place.

As this new model of meshed, ad-hoc network devices presents a shift in how we employ our networks, the concept of network management must also shift in how we view planning and maintaining networks. This research describes a communication framework and network management system (NMS) that supports the design of network aware systems that enable a robust self-management capability in MANETs.

14. SUBJECT TERMS Network Management System, NMS, Tactical Mobile Ad hoc Networks, MANET, Agent-based, Policy-Based, Distributed Networks, Autonomic Networks

15. NUMBER OF PAGES
91

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

DISTRIBUTED AGENT-BASED NETWORKS IN SUPPORT OF ADVANCED MARINE CORPS COMMAND AND CONTROL CONCEPT

Joseph W. M. Rivera
Captain, United States Marine Corps
B.A., University of Washington, 2002

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN INFORMATION TECHNOLOGY MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
September 2012

Author: Joseph W. M. Rivera

Approved by: Alex Bordetsky
Thesis Advisor

John Looney
Second Reader

Dan Boger
Chair, Department of Information Sciences

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The capabilities that Mobile Ad Hoc Networking (MANET) technologies can provide to the Marine Corps are just fully coming into view. These new capabilities represent a much more apparent symbiotic relationship between maneuver at the tactical level and the capabilities of a network that supports that maneuver. However, in order to properly leverage these capabilities, a paradigm shift in what networks are and how they are managed must take place.

As this new model of meshed, ad-hoc network devices presents a shift in how we employ our networks, the concept of network management must also shift in how we view planning and maintaining networks. This research describes a communication framework and network management system (NMS) that supports the design of network aware systems that enable a robust self-management capability in MANETs.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

ADMA	Autonomous Decentralized Management Architecture
ANMP	Ad hoc Network Management Protocol
C2	Command and Control
CBR	Case-Based Reasoning
CCIR	Commander’s Critical Information Requirements
COA	Course of Action
COC	Command Operations Center
COCOM	Combatant Command
COI	Condition of Interest
CWIX	Combined Warrior Integration Exercise
DHS	Department of Homeland Security
DPA	Domain Policy Agent
DPR	Distribute Policy Repository
DRAMA	Dynamic Re-addressing and Management for the Army
DTCS	Distributed Tactical Communications System
ECA	Event-Condition-Action
ECO	Enhanced Company Operations
EM	Electro-Magnetic
EMO	Enhanced MAGTF Operations
GPA	Group Policy Agent
GUI	Graphic User Interface
JIFX	Joint Interagency Field Exploration
LOE	Limited Objective Experiment
LPA	Local Policy Agent
LPDP	Local Policy Decision Point
LPI/LPD	Low Probability of Intercept / Low Probability of Detection
M&S	Modeling and Simulation
MAGTF	Marine Air-Ground Task Force
MANET	Mobile Ad Hoc Network
MCCDC	Marine Corps Combat Development Command

MCWL	Marine Corps Warfighting Lab
MIB	Managed Information Base
MIO	Maritime Interdiction Operation
NGC2	Next-Generation Command and Control
NMS	Network Management System
NMS-TM	Network Management System – Tactical MANET
NOC	Network Operation Center
OID	Object Identifier
OSI	Open System Interconnect
PBNM	Policy Based Network Management
PEP	Policy Enforcement Point
PLI	Position Location Information
RF	Radio Frequency
SATCOM	Satellite Communication
SDR	Software Defined Radio
SI	Swarm Intelligence
SLA	Service Level Agreement
SNMP	Simple Network Management Protocol
SNR	Signal-to-Noise Ratio
SoM	Scheme of Maneuver
SWAP	Size Weight and Power
TSM-E	Tactical Scalable MANET - Enhanced
TW	TrellisWare
TW-230	TrellisWare - 230
USMC	United States Marine Corps
VIRT	Valued Information at the Right Time

I. INTRODUCTION

A. THE EVOLUTION OF MARINE CORPS COMMAND AND CONTROL

For more than a decade, the armed forces of the United States have been involved in actions with non-state actors across a broad spectrum of operations. These operations appear to benefit from dynamic, distributed, and increasingly sustained independent operations by lower echelons of command (Conway 2008). In response to recent lessons learned, the United States Marine Corps (USMC) shifted from the battalion being the smallest echelon of command capable of sustained independent operations to the company (Conway 2008).

Building upon this core concept, the Marine Corps has developed the concept for Enhanced Marine Air Ground Task Force (MAGTF) Operations (EMO)/Enhanced Company Operations (ECO) to organize the Marine Corps to fit this new era of warfighting. The intent of the EMO/ECO concept is to drive development, training, organizing, and equipping of Marines to enable company-sized MAGTFs. In essence, EMO/ECO describes "an approach to the operational art that maximizes the tactical flexibility offered by true decentralized mission accomplishment, consistent with commander's intent and facilitated by improved command and control, intelligence, logistics, and fires capabilities" (Conway 2008).

This approach outlines the need for a profoundly robust, on-the-move communications capability for disparate networked tactical nodes; however, the Marine Corps has yet to fully implement such a distributed and infrastructure-less communications network. Therefore, researchers must first conceptualize a new model for tactical communications. The communications architecture must be one that fundamentally mirrors this inherently ad hoc employment concept and is robust enough to scale effortlessly. An increasingly viable communications archetype that should support the EMO/ECO employment concept is the Mobile Ad hoc Network (MANET). Network devices such as radios, unattended sensors, and other mobile platforms that autonomously and dynamically establish network connections amongst themselves characterize a MANET. These devices will typically form a mesh network topology that does not rely on an established wired infrastructure to maintain those networks, and can remain active indefinitely, as the situation requires.

MANETs are a natural choice to facilitate networking at the *tactical edge*: they enable the dynamic establishment and disestablishment of networks on demand as the operations dictate. As detailed in the most recent Marine Corps Science and Technology Strategy document, the Marine Corps will "develop technologies to provide seamless, automated, self-healing mobile ad hoc networks and network management" (Mills 2012). The Marine Corps clearly sees that the concept of a MANET naturally fulfills a critical component of its evolving communications architecture capability and that MANETs will be the de facto implementation for tactical communications.

B. EMPLOYING TACTICAL MOBILE AD HOC NETWORKS (MANET)

While not fully implemented, the Marine Corps is moving forward with its plans for implementing MANET technologies. These efforts primarily focus on supporting communications at the company level and below. At these levels, there are several key factors regarding communications platform: size, weight, and power (SWAP), scalability, restricted bandwidth, security, and network availability. Taking into account these critical factors, an optimal MANET capability must be able to scale quickly, provide enough bandwidth to support voice and data requirements, and deny the enemy the ability to access or deny those network services.

The Marine Corps Warfighting Lab (MCWL) performed rigorous experiments to develop capabilities that support ECO, and is the driving force in developing the Marine Corps' MANET capabilities (Matkins 2010). MCWL identified a small family of network devices systems that meet the key performance factors of MANETs at the lowest echelons of command and control

(C2), while bridging communications to adjacent and higher echelons of command. Figure 1 illustrates this concept. In the graphic, ground units are connected via a mesh network, and that network is interconnected via high-altitude platforms and satellite communications to other remote ground units and naval operating forces. This provides for robust information exchange capabilities at the tactical level, while enabling integrated command and control with adjacent and higher echelons of command.

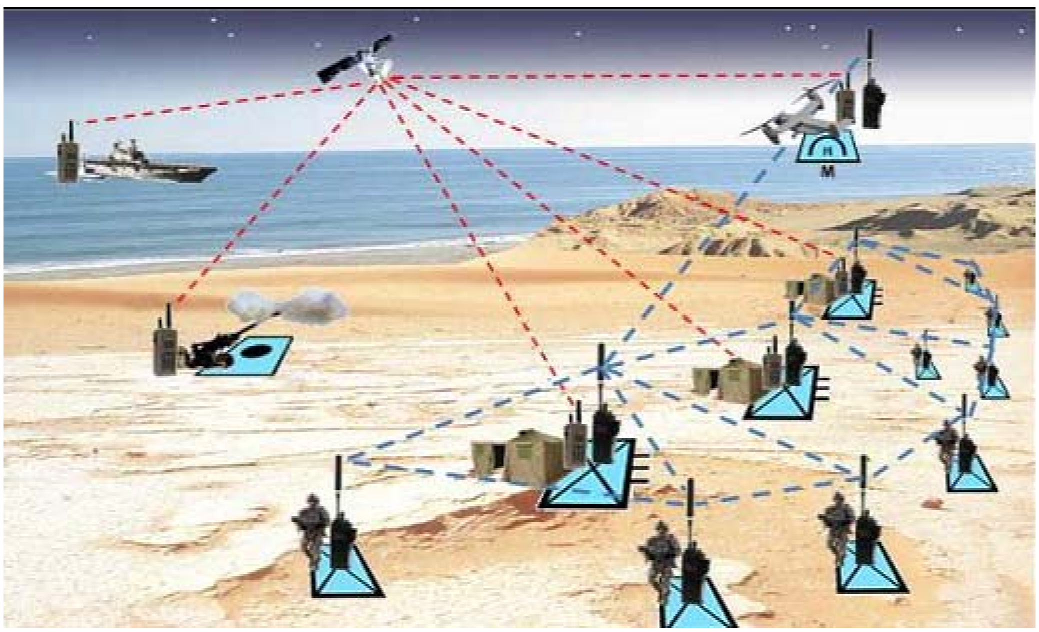

Figure 1. USMC EMO/ECO conceptual MANET employment (From Mills 2012)

The depicted systems are still experimental, but they met all preliminary performance requirements in extending meshed voice/data networks to subordinate elements within a company (e.g.,, fire teams). However, though those systems met the initial experimentation requirements, refining the concept and developing the larger C2 system that they support remains an ongoing effort. The Marine Corps Combat Development Command (MCCDC) set the strategy for developing C2 concepts. C2 systems must "provide a shared understanding of the battlespace…that multiplies combat power…via an adaptable, distributive, and seamless system" (Mills 2012). Understanding this intent and linking it with the emergence of extensive ad hoc mesh networking at the tactical level, there is a need to examine the implementation of more advanced network management paradigms to meet the changing operational concept.

C. EVOLVING MARINE CORPS TACTICAL NETWORK MANAGEMENT CONCEPTS AND EMPLOYMENT

Despite the movement towards implementing the EMO/ECO concept, the Marine Corps' current network management concept and capabilities fall short of achieving its vision. This is due in large part to the lack of a fully integrated tactical network and network management system (NMS) capable of supporting near real-time operational and network management information at the company level. Current NMSs in use at the company level are rudimentary because they typically support only small, static data networks. These systems do not easily scale and do not incorporate the constantly changing environmental factors (e.g.,, constant physical compression and expansion, radio frequency (RF) interference, atmospheric effects) inherent in tactical operations. This lack of a fully integrated NMS limits decision-making and situational awareness at the lower levels, and limits geographically dispersed military forces from leveraging the enhanced warfighting capacity envisioned by EMO/ECO.

Network management systems must "provide technologies that include the capability to employ Modeling and Simulation (M&S) techniques to evaluate network performance, enable automatic recovery, alerting, and net intrusion countermeasures; and graceful network reconfiguration and/or degradation as nodes are lost and recovered" (Mills 2012). This implies that an NMS must now integrate into many facets of kinetic operations, from wargaming courses of action (COAs), to dynamically accounting for network gaps, and changes in the scheme of maneuver as they occur. What this means to the warfighter is that kinetic operations and the networks that support them are now becoming increasingly symbiotic. Such highly dynamic and complex activities as combat operations are increasingly dependent on the networks that support them, especially in the force employment scheme envisioned by EMO/ECO. Likewise, the capabilities of those same networks are entwined with the scheme of maneuver that they support.

1. Symbiosis of Network and Scheme of Maneuver

The scheme of maneuvers associated with ECO portends a new level of interdependence between command and control (C2) systems (i.e.,, the combination of technologies, people and procedures) and the networks that support them. This research envision that operators and managers instigate the network management concept from the bottom up in conjunction with the dynamics of battlefield decisions regarding elements like scheme of maneuver. In traditional network architectures, the preponderance of the network's capacity originates from higher echelons of command with their larger capability sets, and filters down towards the lower echelons of command: the communication networks are designed to meet the largest breadth of operational requirements with a focus on capability at the higher echelon command operations centers (COC). In other words, command, control and communications systems are primarily designed to support the higher echelon commanders' requirements; it is not usual to consider units at the company level and below as sources of strength for the network, but instead as ancillary customers. Communications planners, therefore, regulate most information exchange requirements at those lower echelons to simple broadcast voice and extremely limited data access.

In the new distributed, highly dynamic, adaptive, ubiquitous presence network concept, the strength of the network lies with the nodes that comprise the physical edge of the network. Thus, network management should begin at the lowest maneuver elements to facilitate coordination of decentralized operations; and as such, a true paradigm shift in the concept of what C2 means at the company level. It requires a shift away from the model that a communications planner builds C2 networks in response to a previously established Scheme of Maneuver (SoM): operational planners develop the SoM independent of the network that will support it. This paradigm shift leads planners to realize that the maneuver elements' scheme of maneuver and the network are reciprocally interdependent. The network and SoM are symbiotic in that they mutually support each other, and vulnerabilities in one directly affect the other. This interdependency represents a change in how planners approach the design of their communication architectures, especially in the case of EMO/ECO requiring the high integration of all the warfighting functions across an exceedingly distributed command and control structure. With the emergence of EMO/ECO concepts and plans, the network is now a key defining characteristic of the commander's capabilities and limitations. As such, the management of the network represents a central enabling feature required for realizing EMO/ECO's premise of sustained, distributed, and independent operations at the company level across the full spectrum of operations.

Evolving the network concept for EMO/ECO not only requires an evolution in how the Marine Corps conceptualizes management of the network, but must also include the technologies (e.g., devices) that actually comprise the network. While it is apparent that mobile ad hoc networks will be prevalent at the tactical level, an examination of what those devices within the mesh network represent must also take place. Following the premise that the scheme of maneuver and the network are highly interdependent, it logically follows that every actor at the maneuver element (e.g., a Marine, a vehicle, or a sensor) represents a physical node on the network. Taking the assumption that most actors within the SoM will be Marines, sentient beings that actively participate in their environment, each individual Marine will have a mirrored presence by a node on the network. This means that each network device on the mesh must exhibit some level of self-awareness and cognizance in order to react and adapt to their surroundings; becoming active participants in their environment.

2. Hypernodes and the Emergence of Context-Aware, Agent-Based, Policy-Driven Network Paradigms

To more accurately represent the environment that the MANET will operate in, and manage the network they comprise, the nodes that comprise the mesh must exhibit some capacity for self-awareness and cooperative management. Enabling some capacity for configuration, coordination, and management amongst nodes, without operator intervention is critical in this respect. It is both implausible and impractical for a singular network operations center to account for the amount and scale of variation inherent in a MANET; thus, it becomes apparent that the nodes themselves (as active participants in their environment), become active agents in the network management activity.

Developed at the Naval Postgraduate School, the *8th layer concept* provides the framework for imbuing this notion of self-aware, self-controlling functionality. By including an additional layer to the standard Open Systems Interconnect (OSI) 7 layer model that takes into account human and organizational factors, this additional layer enables this self-aware, self-controlling capability, known as *adaptive networking* (Bordetsky and Hayes-Roth 2009). This enhanced capability requires a new communications protocol and architecture that enables each node to have its own specialized Network Operations Center (NOC) capability. Those nodes, known as *hypernodes*, that contain this adaptive NOC capability incorporate a Sense-Analyze-Adapt feedback loop (Figure 2) and form the building blocks of adaptive networks (Puff 2011).

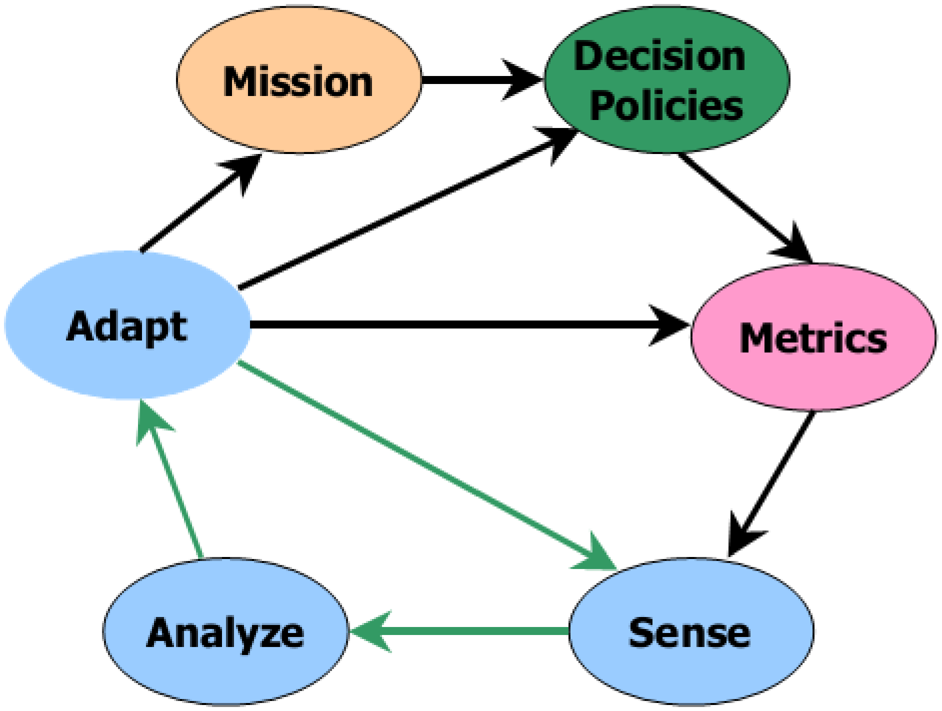

Figure 2. NOC process model (From Boredetsky, Dolk, and Zolla 2004)

Essentially, each hypernode represents an intelligent agent on the network and these "Intelligent agents [agent-based] can then be defined as a … device that can recognize its environment information, make sense of the context [context-aware], perform plausible reasoning, and decide on courses of action while collaborating with other agents" (Ntuen and Kim 2011).

To incorporate this concept into military-specific applications this thesis introduces the application of a *policy-driven* functionality. In this thesis, the term "policy-driven" describes the execution of mission-type orders in hypernodes. In mission-type orders, the commander gives subordinates a clearly defined goal (the mission). Framing that mission, the commander issues a *commander's intent* statement that defines the desired endstate and specifies any restraints and constraints regarding accomplishing that mission. Furthermore, the commander can also issue Commander's Critical Information Requirements

(CCIRs), which detail general instructions and key information flows pertinent to the intent. At that time, the subordinate leaders then implement the order independently with a large degree of freedom in execution, as long as they meet the commander's intent and communicate those CCIRs as appropriate. This operational concept allows a high-degree of flexibility of execution at the tactical levels while freeing the higher leadership from becoming marred in tactical details, hence facilitating much more efficient and effective management of the larger Scheme of Maneuver.

A similarly intent driven agent-based, policy-driven network management model executed within network devices capable of supporting the hypernode concept in MANETs represent an evolution in network management, especially at the tactical level of combat operations. Since hypernodes in the MANET now represent active participants in the network management role, the activity of network management is distributed across the entire network; whereas, the traditional network management model focuses on issuing reactive top-down orders to network devices. The rapid growth in the number of devices combined with the dynamic and uncertain nature of tactical operations in a crisis makes this network management model untenable.

3. Autonomic Network Management

Another term to describe the family of devices that hypernodes represent is *cognitive radio*. A cognitive radio, and by extension a cognitive MANET, is an intelligent wireless communications device or network based on a software defined radio that is aware of its environment and can adapt to variations to its inputs (Potier and Qian 2011). In traditional network management, the system monitors and reports key network metrics (e.g., bitrate loss, throughput) that would prompt an operator to take some action (e.g., turn off services, reroute traffic). In contrast, *autonomic networks* provide a framework for nodes to acquire, predict, verify and *autonomously* act on network information. The nodes would essentially self-adapt and act in response to network behavior in order to meet specific action criteria affecting various network management components (Figure 3). In autonomic network management, these specific action criteria are those mission-type orders previously described.

Network Management Component	Wired Traditional Network	Wireless Cognitive Radio Ad Hoc Network
Performance Management	Monitor performance and throttle resources	Proactive and reactive performance control with dynamic bandwidth allocation
Fault Management	Identify, isolate and clear faults	Manage highly variable link quality, channel acquisition after PU interruption
Security Management	Control network access, Protect against intrusion, tampering, spoofing	Control network access and routing, Mobility handling, Protect against intrusion, tampering, spoofing
Configuration Management	Setup equipment configuration, Update software versions	Update network for nodes that move, power-off or die, Spectrum sensing and utilization
Accounting Management	Track resource utilization, Allocate resources per Service Level Agreements	Accounting/billing used with Performance Management for Quality of Service agreement

Figure 3. Cognitive Networks versus Traditional Networks (From Potier and Qian 2011)

Since these specific action criteria represent the mission critical variables for a commander, clearly defining those criteria become a key enabling component for implementing the autonomic networking concept. Another key aspect of autonomic networking is the hypernode's capacity for *predictive reasoning*. By being able to predict changes in those critical criteria, a hypernode is able to anticipate its own NOC's activities and, in theory, coordinate those actions with other nodes before that event occurs. Decision support system such as Case-Based Reasoning would enable predictive capabilities through the replay of previously recorded cases for forecasting future or planned network coverage in unknown situations based upon knowledge learned from previously recorded experiences (Puff 2011).

D. SUMMARY

Improving Command and Control (C2) is a central effort in the development of an EMO/ECO capability envisioned by the Marine Corps

Warfighting Lab (MCWL) (Price and Mchuen 2009). The groundwork for developing the concept of a holistic Network Management System (NMS) to enhance EMO/ECO C2 is discussed in a recent NPS thesis—see Puff, 2011. This research thesis continues that work by building upon current cognitive network management models, predictive behavior analysis techniques and algorithms, and the 8th Layer hypernode concept. The intent is to develop a framework and operationalize those concepts for tactical networks that will support the implementation of EMO/ECO concepts and strategy.

THIS PAGE INTENTIONALLY LEFT BLANK

II. NEXT GENERATION NETWORK MANAGEMENT DESIGN CONCEPTS

The management of MANETs at the tactical level present some unique challenges not faced by traditional network management practices and systems. Most traditional network management schemes employ a centralized management structure that typically requires detailed and accurate knowledge about the network. These centralized network management systems work best in networks where the structure and operating environment are relatively static. Mobile ad hoc networks are typically highly scalable, decentralized, and dynamic; that requires a much different approach to network management. Furthermore, MANETs in tactical combat environments intensify those challenges by introducing a greater degree of dynamism. To better meet the challenges of on-going and future combat operations, a new-conceptualization of the composition and role of those command and control (C2) networks that support combat operations at the tactical level is needed. This chapter first addresses the current operational and technical Command, Control, Communications, and Computers (C4) vision of the Marine Corps. This vision needs to identify the key challenges, concepts, and enabling technologies associated with MANET technology and management. From this, the thesis introduces various operating models, network architectures, and management frameworks that serve as enabling factors to meet the demanding needs of a robust network management concept for tactical level MANETs.

A. EVOLVING MARINE CORPS COMMUNICATION C4 STRATEGY AND CONCEPTS

1. Key Concepts for Marine Corps Tactical Command and Control In Support of EMO/ECO Objectives

The concept of Enhanced Company Operations is part of a much larger, continuously evolving Enhanced Marine Air-Ground Task Force (MAGTF) Operations (EMO) concept. The purpose of EMO has many different aspects, addressing the entire spectrum of capabilities within a MAGTF. Within this concept, several objectives are key:

- Operate in a distributed environment where information and communications may be limited or non-existent and thus require informed decision-makers at the lowest echelons of command
- Overcome challenges to access[1] and mobility, and when necessary employ decentralized operations to assure access through multiple entry points. (Flynn 2010)

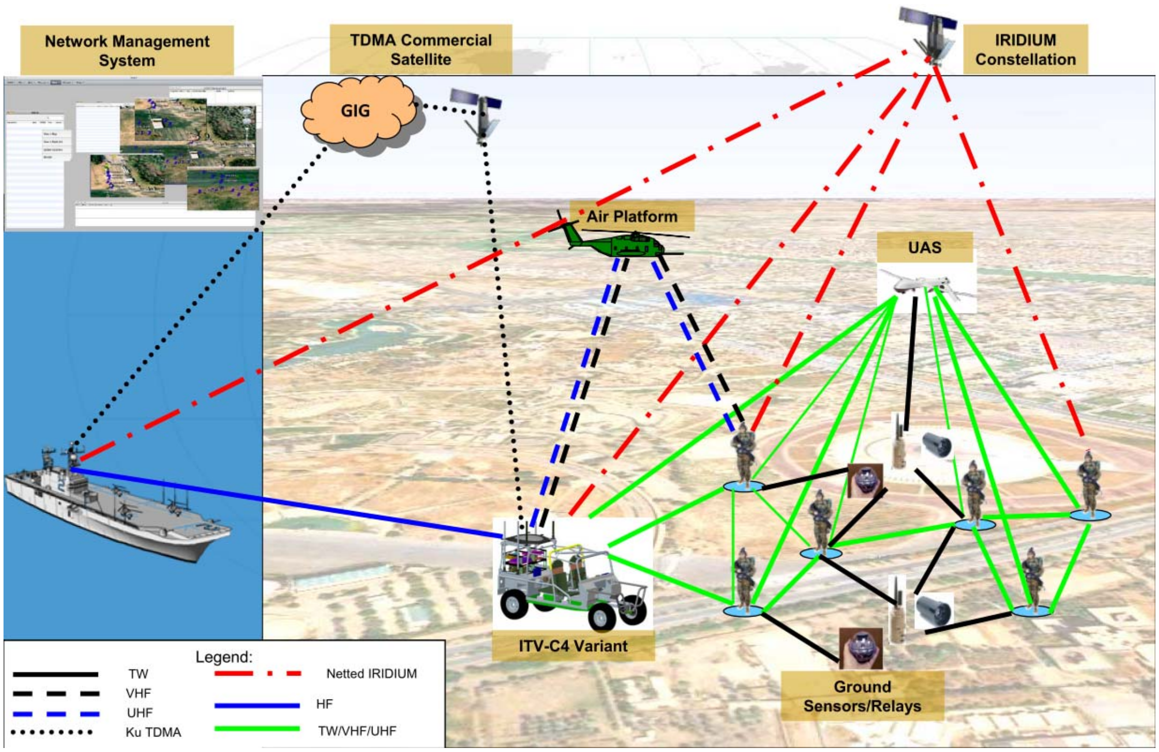

Figure 4. Concept for Enabling Advanced C2 (From Goulding 2012)

As part of addressing these key operational considerations, MCWL has developed a conceptual framework advancing C2 in support of EMO (Figure 4). Part of a much larger C2 architectural concept, MANET plays a significant role in the tactical-level C2 architecture. The challenges at this level emanate from high mobility, uncertain terrain, and a highly disruptive radio frequency (RF) environment. Furthermore, these tactical-level operations are integral to

[1] Access: military movement into a theater of operations

decentralized operations; thus, entailing the need for C2 architectures that not only reach down to the individual Marine, but interlink various echelons of command and control seamlessly. MCWL has done extensive research through a series of Limited Objective Experiments (Matkins 2010) on the proper enabling technologies to operationalize the conceptual framework—those technologies will ultimately fall into the hands of individual Marines.

2. Marine Corps Experimental Command and Control Network Architecture

In 2010, MCWL performed a series of experimentation designed to test the viability of various MANET technologies and receive feedback from a typical Marine infantry unit on its practicality in the field (Matkins 2010). Within this line of experimentation, MCWL experimented with two leading MANET solutions for the platoon level that comprised part of the Next-Generation Command and Control (NGC2) program, the Distributed Tactical Communications System (DTCS), and the TrellisWare CheetahNet (TW). DTCS leverages the existing Iridium satellite constellation system to provide a "netted Iridium" solution that creates a meshed radio network for ground units. DTCS leverages the potential for beyond line-of-sight geographically distributed operations by using GPS satellites for establishing ground networks. CheetahNet in contrast, does not depend on any existing infrastructure to establish a localized mesh network and those networks have a robust self-forming and self-healing capability. This essentially enables the dynamic formation of networks with minimal lag (i.e., networks can be rapidly created, fragmented into multiple operating networks, and reassembled). This capability is critical to meet the demands of a highly dynamic operating environment, where information exchanges through ubiquitous networks are seamless to the operator. For this reason, MCWL has adopted TW to represent the last mile in extending communications to the individual Marine (Matkins 2010).

3. Furthering Marine Corps Experimental Command and Control Concepts

As part of the effort to extend the networking down to the individual Marine, MCWL is developing the tactical MANET network management system (NMS-TM) for the NGC2 radio systems (Donnelly 2010). The primary objectives of this network management system are to allow users to “predict, monitor, and control network behavior; this specifically includes viewing and remotely managing variables such as node status, node location, attached equipment, channel selection, frequencies, error rates, and network utilization” (http://www.marines.mil/unit/mcwl/Pages/C4.aspx) MCWL is also working with the Naval Postgraduate School to explore the inclusion of *8th Layer* concepts (see Bordetsky and Hayes-Roth 2009) to enhance the prediction, monitoring, and control aspects of NMS-TM. Some specific objectives of this investigation include (Puff 2011):

1. Explore bandwidth adaptive solutions for hypernodes to adjust their network loads at the application layer.

2. Examine how to make NMS-TM alert the user regarding the geographic adjustment of nodes to improve overall network performance.

3. Research how hypernodes can support sensors to intelligently send data based on link health, network health, and bandwidth availability.

4. Examine how hypernodes on the move can propagate sensor data in relation to link health and bandwidth availability.

This study continues this investigation of the base hypernode concept by incorporating agent-based, policy-driven network management models and concepts. As discussed earlier, this assumes a naturally emerging symbiosis between the scheme of maneuver and the command and control systems at the tactical level. The design of a next-generation command and control system for the Marine Corps that melds C2 and maneuver suggests a bottom-up approach that focuses on the individual as the source of all action. Thus, this new approach to network management begins by finding a means of combining the radio operator, network operator and technical aspect of the devices themselves.

B. TACTICAL NETWORK MANAGEMENT CHALLENGES AND ENABLING CONCEPTS

1. Key Challenges in Tactical Network Management

Because MANET technologies are inherently independent of fixed infrastructures and can dynamically create networks as the need arises, they are a natural fit for tactical-level operations that are often highly distributed and take place in locations where existing infrastructure either does not exist or is unsustainable. The diversity, scale, and unique dynamic nature of tactical MANET solutions require planners to assume similarly unique considerations in their employment and management.

a. Constraints and Restraints Inherent in Tactical Networks

The primary constraint in most tactical environments is that networks and their constituent devices (e.g., routers, switches, servers) have to operate in resource-constrained environments. This constraint is the direct relationship that throughput and availability are relative to the size, weight, and power considerations of devices when implementing within the framework of dismounted operations. A device that can transmit at 1000 watts may be optimal to cover large distances and provide more than enough throughput, but the weight requirement for such a device would most likely make it non man-portable due to the weight and size of the power supply and amplifier. Thus, man-portable devices with smaller power supplies that have a smaller power output (consequently, lower throughput and range) will be a primary driver of SWAP planning considerations.

Furthermore, tactical operations typically occur in extremely volatile environments where RF and Electromagnetic (EM) interference and atmospherics have a large impact on RF propagation. Combining the low transmission power with a high interference environment and RF propagation in a tactical wireless network is further restrained. These considerations restrain throughput as managers implement lower transmission power and secure transmission methods to meet the need for Low Probability of Intercept/Low Probability of Detection (LPI/LPD). Figure 5 illustrates all these considerations. As these restraints and constraints acting on the network serve to weaken the overall potential quality and availability of network resources, managers must consider this fact as the driving planning factor for their networks.

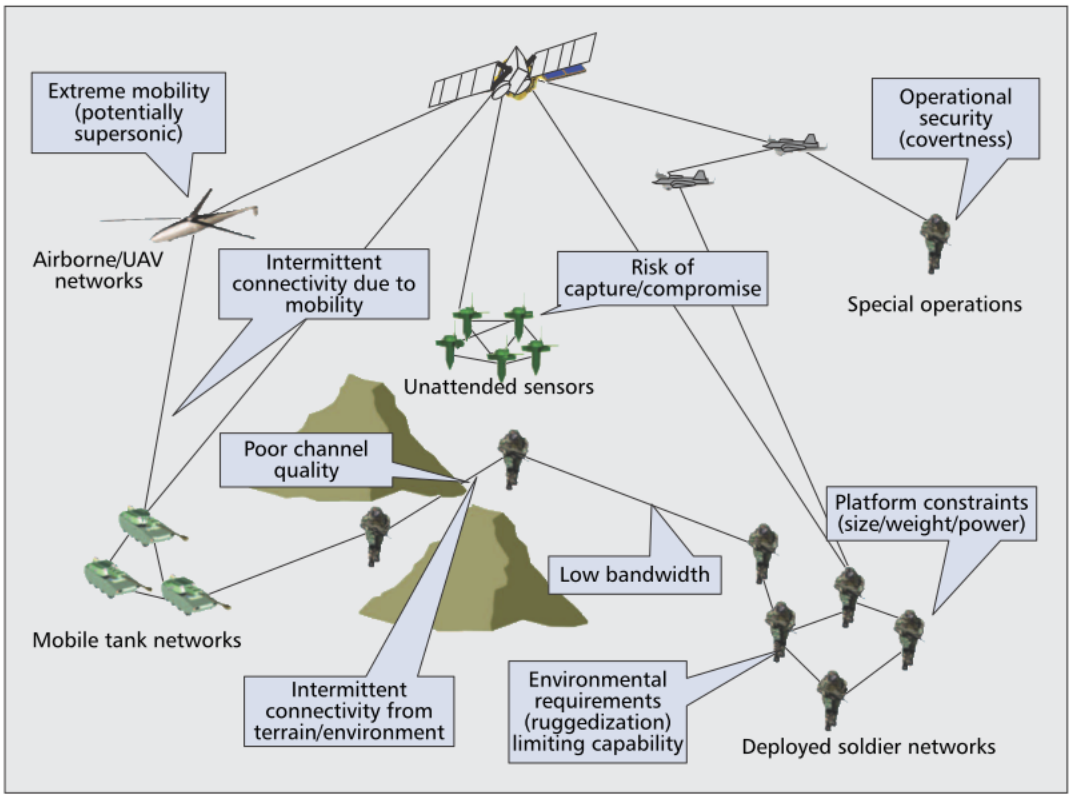

Figure 5. The constraints of the tactical military environment (From: Burbank et al. 2006)

The inherent feature of a self-forming and self-healing network in MANETs also becomes a planning consideration. Since MANET nodes can autonomously join, disassociate, and re-join networks, traditional network management models are insufficient as the number of nodes in the mesh increases (El brak et al. 2011). This dynamism of node control and management presents unique network management challenges in ad hoc networks.

b. Ad hoc Network Management Challenges

Though MANETs may physically resemble flat architectures, where all network devices are directly linked to each other and interconnect via bridges (Figure 6), approaching management from the perspective of a flat network becomes problematic. Due to the potentially large scale of MANETs, performance of the network and its management systems suffer because of the accumulative management overhead from maintaining the mesh, routing, individual node control functions, and other network management functions. Furthermore, considering highly dynamic and demanding environmental conditions that exist at the tactical level, the difficulty in predicting and managing network behaviors in a MANET becomes untenable, as the calculations required to predict and management network behaviors in a MANET become excessive. For effective management of such a large amount of management data and processes, it is intuitively apparent that the scope of network management must have some mode of compartmentalization. This implies that managers must implement some new organizational model of network management for proper handling of the scaling and vigorous computational requirements inherent in MANETs.

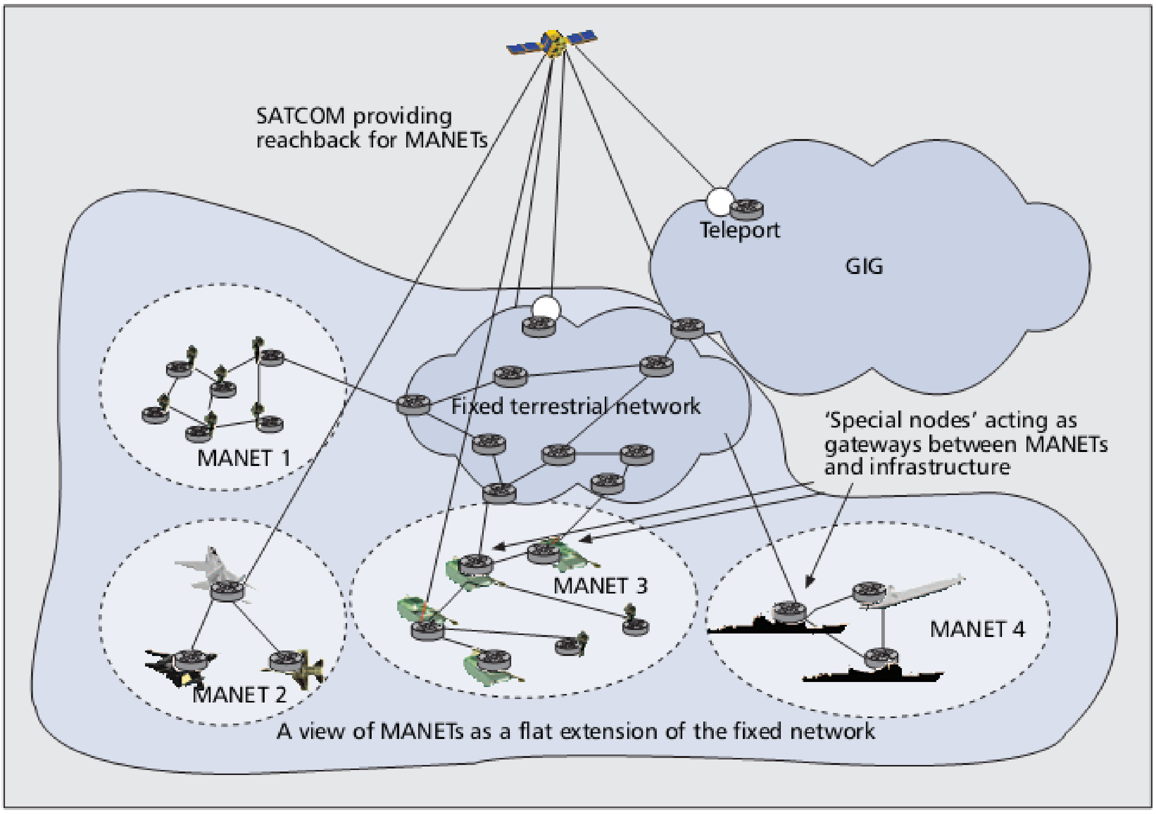

Figure 6. A view of MANETs as a flat extension of the network infrastructure (From Burbank et al 2006)

Since nodes are both mobile and typically in rich scattering environments, link-level connectivity is unreliable and the network topology is highly dynamic (Halford and Chugg 2010); therefore, the characteristic self-forming and self-healing capabilities of TW MANETs become a further key consideration where networks can be disconnected from the larger network for various periods. Because most network monitoring schemes rely on consistent and reliable communication with network elements, traditional network management systems (especially centrally managed systems) do not sufficiently cope with monitoring and managing network elements that consistently establish and disestablish from the NMS. Due to these inherent operating considerations, dynamic and distributed networks such as MANETs require management capabilities that are likewise distributed in nature (Burbank et al. 2006).

As discussed before, it now is apparent that applying a traditional top-down, centralized approach to management is unsound in the case of MANETs. The management challenges for MANETs require a bottom-up, decentralized approach that considers the tactical maneuver element as an integral piece to the management solution. In this view, the network is an active tangible participant in its environment, not a passive ephemeral service. Developing this framework of network management requires the examination of how to integrate several enabling concepts to comprise a true next-generation command and control system. Critical elements of such a system will include a distributive network management paradigm, robust MANET technologies such as CheetahNet, application of the hypernode concept, and a predictive mechanism that enables an adaptive NMS capability.

2. Enabling concepts

a. Distributive Network Management

> As joint land operations tend to become decentralized, mission command becomes the preferred method of C2. Mission command is the conduct of military operations through decentralized execution based upon mission-type orders. Successful mission command demands that subordinate leaders at all echelons exercise disciplined initiative, acting aggressively and independently to accomplish the mission. Essential to mission command is the thorough knowledge and understanding of the commander's intent at every level of command. Under mission command, commanders issue mission-type orders, use implicit communications, and delegate most decisions to subordinates wherever possible. (Joint Publication 3-31 2010)

A key operational concept in conducting distributed operations is the effective execution of mission-type orders. Joint Publication 3-31 describes why and how mission-type orders are the preferred method of C2 in decentralized (i.e., distributed) operations. By definition, EMO/ECO has the defining characteristic of decentralized command and control and accedes to the tenets outlined by mission-type orders: commander's intent, implicit communications, and initiative-driven action. The translation of the core principles from mission-type tactics towards network management is attained by implementing networks where each device has a measure of self-cognizance and situational awareness and can act independently or in concert with peers based on restraints and constraints identified in mission-type orders from an assigned commander. This resembles the concept of a distributed network management model. This model employs multiple manager stations where each manager independently controls a sub network and may communicate directly with other manager stations (El brak et al. 2011). In this way, distributive network management closely mimics the autonomic and dynamic nature of mission-type tactics. In implementation, however, distributed MANET network management systems must perform management functions without a static infrastructure (i.e., deploy with an organic management capability).

b. Infrastructure-Independent Networks

Implementing network management at the tactical level begins with understanding that distributed operations, as envisioned by EMO/ECO, do not require an existing infrastructure for support of combat troops. Those troops are typically self-sufficient and do not need existing logistical support to commence operations. Tactical networks must mirror this independence from existing infrastructure and be able to create and reconfigure, as needed, its own network topography and management infrastructure. The Marine Corps Warfighting Lab has identified MANET technologies such as TrellisWare CheetahNet (TW-230) as the surrogate technology for developing enhanced ad hoc intra-/inter-platoon communications. The TW-230's use TrellisWare's Tactical Scalable MANET-Enhanced (TSM-E) waveform that provides extremely robust self-forming and self-healing characteristics. Furthermore, the TW-230 is able to scale extremely well (i.e., incorporate thousands of nodes concurrently) and operate in difficult multipath environments through its use of barrage relay technologies. This technology allows the TW-230 to resolve multiple transmissions from multiple sources as multipath components of the same signal. It is able to employ the simplest type of algorithm for packet routing: each radio re-transmits every packet it receives (Puff 2011). In this way, every Marine on the mesh network can potentially serve as a repeater for every other connected node on the mesh. The capabilities represented in the TW-230 meet a great deal of the requirements inherent in tactical man-portable communications: lightweight, low power (2W maximum transmission rate), resistance to RF interference, and excellent scalability. The TW-230 is also a software-defined radio (SDR): it provides concurrent voice and data service through a programmable interface, and capabilities for self-configuration. Just as tactical MANET systems must deploy their architecture independent of existing infrastructure; they must also deploy their own management framework independently. Next is a discussion of this aspect of collective self-management by examining the models of autonomic computing and cognitive networks.

c. Autonomic Operations and Cognitive Networks

In a cognitive network, each node in the system is responsible for monitoring local network behavior and adjusting operational parameters based on mission policies. In addition, cognitive nodes have the ability to learn new policies that can be shared with other nodes, improving their ability to adapt to similar network conditions in the future (Vanderhorn et al. 2010). This builds on the distributive model of network management by moving the management function to every node in the network, vice to predetermined managers (i.e., typical centralized network management systems). Through this framework, network management truly begins from the bottom-up. Every node is a manager and cooperatively works with every other node to satisfy network features such as topology and reliability. Furthermore, by localizing the network management function across all nodes within the network, the dependency of nodes to a central NMS is reduced.

Cognitive networks propagate knowledge of the network throughout the nodes, so knowledge is gained, distributed, stored, and potentially acted upon by any network node. This is in consonance with management functions associated with ECO. As the number of nodes within a MANET increases, the growing cost and management complexity of this approach becomes intuitively apparent. Autonomic computing lends towards reducing that cost and complexity of network management (Ayari et al. 2009).

The notion of autonomic operations derives from the observation that the human nervous system. It governs the heart rate and body temperature, thus freeing the conscious brain from the burden of dealing with these and many other low-level, yet vital, functions (Kephart and Chess 2003). In autonomic computing, given some high-level objectives from an administrator, every node manages itself independently, works together with other nodes across the network, and collaboratively decides upon actions that provide benefit to the whole network. Developing an autonomic management framework is an evolutionary process that begins from highly manual operations and progresses towards highly autonomous operations (Hadjiantonis 2012):

- Basic: manually operated management operations.
- Managed: management technologies used to collect and synthesize information.
- Predictive: correlation among management technologies provides the ability to recognize patterns, predict optimal configuration and suggest solutions to administrators.
- Adaptive: management framework can automatically take actions based on available knowledge, subject to the supervision of administrators.
- Autonomic: business policies and objectives govern infrastructure operation. Users interact with the autonomic technology tools to monitor business processes and/or alter the objectives.

This list shows that autonomic operations evolve out of predictive and adaptive network operations by dynamically integrating the network and an organization's business rules and policies without consistent human management (Figure 7). This approach transcends predictive and adaptive management operations because it enables the network as a whole to extend those predictive and adaptive capabilities, thus making the network an integral part in defining and executing the organizational strategy. This reinforces the view that the network and the scheme of maneuver are symbiotic in tactical combat operations.

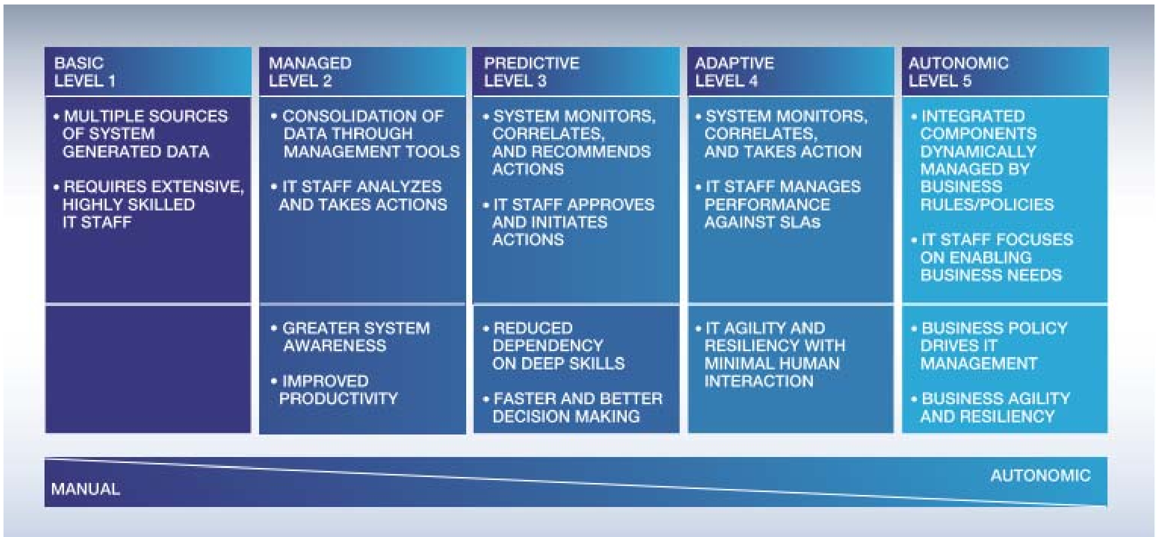

Figure 7. Evolving to Autonomic Operations (From Ganek and Corbi 2003)

Cognitive networks and autonomic operations correspond to the hypernode concept discussed earlier as both require some high-level objectives that define a set of business policies. In the case of tactical network operations, those business policies parallel the mission-type orders that drive distributed operations: they should provide guidance for the policies that the network's management systems attempt to implement.

d. Policy-Based Network Management (PBNM)

In operations governed by mission-type orders, the military commander gives their subordinate leaders a clearly defined mission in sufficient detail to enable subordinate and supporting commanders understand the commander's guidance and intent. With that understanding, subordinates are allowed to build and evolve their supporting plans and actions according to conditions encountered (Joint Pub 3-31 2010). The subordinate leaders then implement the order independently and in consonance with the commander's intent, yet ever mindful of the importance of coordination with supported and supporting commands.

In a policy-based network management framework, a manager translates complex management tasks into a collection of high-level policies that support monitoring of the network and automatically enforce appropriate actions. In general, policies are defined as Event-Condition-Action (ECA) clauses, (e.g.,, where during event E, if condition C is true, then action A is executed) (Hadjiantonis and Pavlou 2009). This closely resembles the previously mentioned Sense-Analyze-Adapt feedback loop that forms the building blocks for an adaptive network management capability. Furthermore, the policies themselves are exclusive of any specific device and should only communicate what should happen in an ECA clause, not exactly how to implement it. This allows an agent (i.e., 8th layer hypernode) to take into context its environment and decide on the best means to fulfill a certain policy. By combining policy-based network management with context-awareness, not only does a PBNM framework enable the translation of commander's intent into network management policies, but also supports the employment of a network that is capable of emulating human cognition by perceiving events and acting upon them in accordance with orders.

Because a policy-based network management framework reflects natural command and control concepts found in tactical combat operations, it is a suitable solution for implementing a highly distributed, robust tactical MANET that autonomously adapts to its environment; thus, complimenting combat operations at the tactical level. Furthering this capability, this research thesis will detail the application of distributive, autonomic networks within the PBNM paradigm as they apply to Marine Corps tactical MANET management.

C. POLICY-BASED AUTONOMOUS NETWORK MANAGEMENT DESIGN FRAMEWORK

The model of a decentralized, policy-based MANET NMS is a critical component of the MCWL NGC2 concept. Without understanding that high-tempo, distributed operations require a similarly distributed network management paradigm, Marine Corps C2 will never fully support the tenets outlined in the EMO/ECO concept. Hence, a principle capability is to develop computing systems that can manage themselves given high-level objectives that reflect the commander's intent. These systems will reflect the coupling of human intuition and decision making with the distributive computational capabilities of a MANET. Indeed, policy as a representation of this human intuition, is not only a basis for, but also *drives* the management capability of these systems. The design of such a system is dependent on two primary aspects: (1) autonomic network architecture coupled with a policy-*driven* self-management framework, and (2) cognitive agents to populate the network and preform the collaborative computing.

1. Network Management Models and Evolving the 8th Layer Concept

The primary challenge of employing a tactical MANET regards how to manage a highly scalable, complex network rapidly and effectively. Management begins with identifying the operating model used in defining a management strategy. There are four major types of operating models: centralized, distributed, hybrid, and hierarchical. Figure 8 illustrates the distributed, hybrid, and hierarchical models applicable to MANETs. In traditional static networks, centralized management architectures are sufficient; however, in the case of MANETs, centralized management becomes untenable due to issues with scalability and addressing the highly dynamic nature of a MANET (Znaty and Martin-Flatin 1997). Hierarchical models are efficient, and closely resemble the natural command and control organizational structure in tactical units where management uses intermediate managers, each with its own management domain (Hadjiantonis 2012). Hierarchical models, however, do not scale well due several factors such as high message overhead, tendency towards single points of failure, and in partitioned networks, some nodes being left without any management functionality (El brak et al. 2011). Distributed operating models are the optimal organizational model for MANETs. They directly correlate to the barrage relay architecture of the TW-230 and are the most accommodating to a self-forming, self-healing network topology. Yet, this purely distributed operating model is incompatible with the employment concepts outlined in EMO/ECO. Though EMO/ECO prescribes a distributed C2 and combat employment paradigm, military unit organizational structures still entail a level of hierarchical organization.

To support tactical combat operations, the appropriate operating model must adopt a hybrid structure between hierarchical and distributed operating models. A recent study on developing policy-based self-management MANET architectures presented such a hybrid model that utilizes clusters of nodes to form a loosely coupled hierarchy that can dynamically adjust between either a purely hierarchical or distributed management topology to a form a hybrid management topology (Figure 8). This model is appropriate because it corresponds more closely with EMO/ECO's C2 structure. Its adaptability is crucial for maintaining a management function that supports the inherent self-forming and self-healing aspect of MANETs.

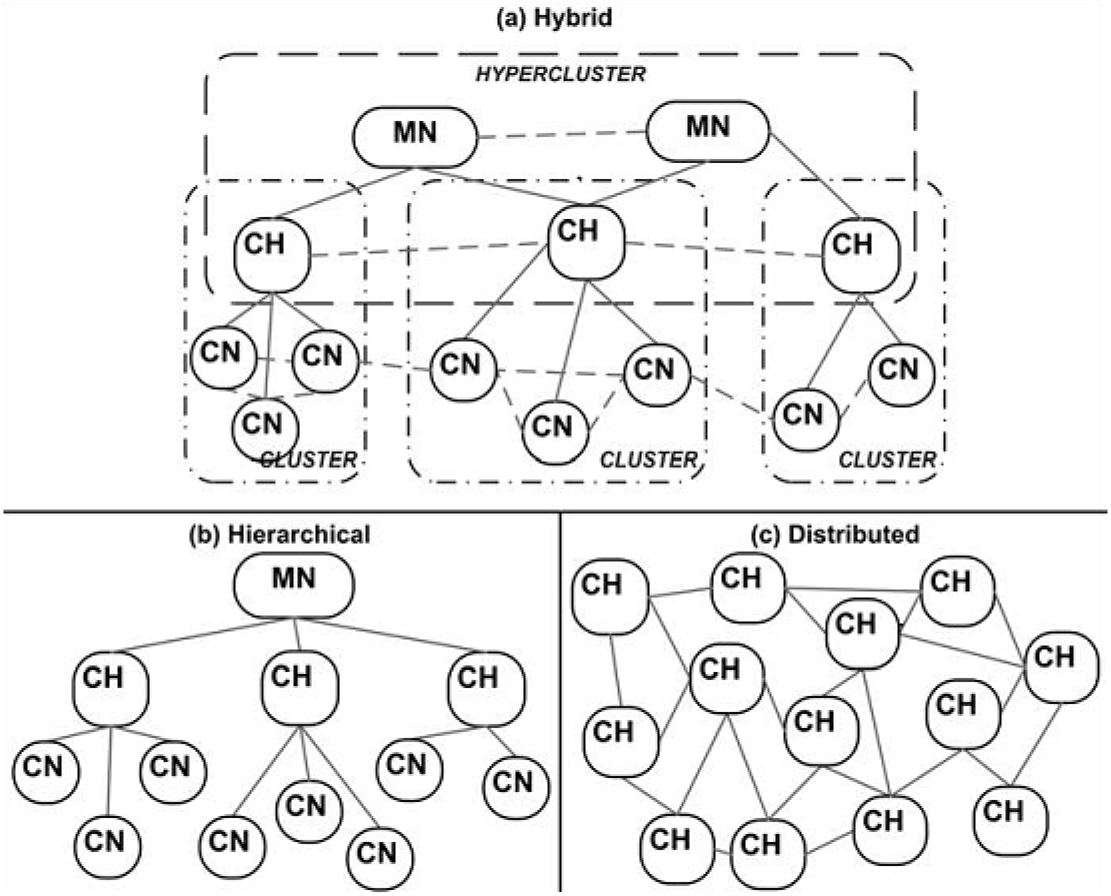

Figure 8. Example of Operating models: (a) hybrid, (b) hierarchical, (c) distributed (From Hadjiantonis 2012)

Having an aligned operating model for a next-generation C2 system, the next step is identifying the underlying management framework within that operating model. The 8th layer/hypernode concept serves as a basis for developing a fully autonomic network management framework. The 8th layer's concepts directly address the need to implement self-forming and self-controlling functionalities needed as part of an autonomic system. It does this by defining a hierarchy of services that lie above the OSI application layer. The 8th layer's network management hierarchy of services (Figure 9) provides individual nodes with the capabilities of self-diagnosis (Network Element Layer), sub-network view (Network Element Management Layer), end-to-end performance (Network Management Layer), Quality of Service requirements (Service Management

Layer), and Service Level Agreement (SLA) negotiation (Business Management Layer). The 8th layer approach also uses a simple network management protocol (SNMP) events monitor with management information base (MIB) extensions in order to incorporate service layer and business layer elements (Bordetsky and Hayes-Roth 2009).

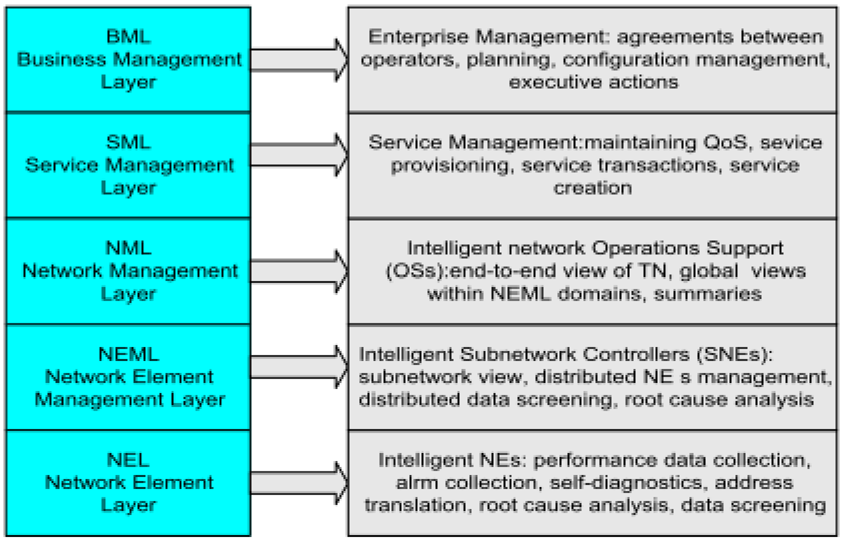

Figure 9. The 8th layer elements (From Bordetsky and Hayes-Roth 2009)

The driving element behind implementing these services is the sense-analyze-adapt feedback loop. These feedback loops reflect basic management processes (Figure 10). At the top levels, this process model must identify the mission or strategic level objectives. Service level agreement (SLA) constraints and performance metrics allow managers to measure the performance against the strategic objectives. This determines the specific variables to reconfigure in order to adapt the network configuration towards a more optimal solution in accordance with the SLA constraints (Bordetsky, Dolk, and Zolla 2004).

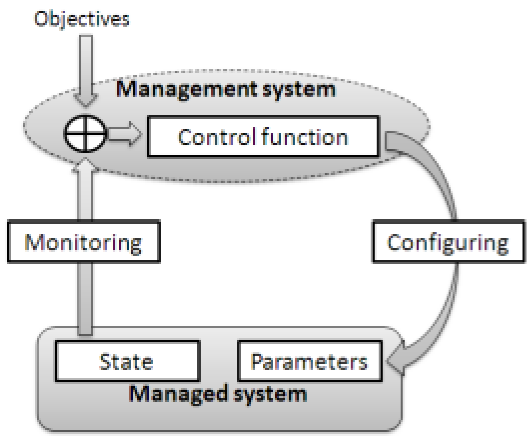

Figure 10. Basic management process (From El brak et al. 2011)

The management protocol used to communicate and manage these reconfiguration activities is the Simple Network Management Protocol (SNMP). The 8th layer uses an SNMP Management Information Base (MIB) framework to allow an NMS to remotely monitor and configure network elements in a manager/agent architecture (Figure 11). Simple Network Management Protocol MIBs are a mature and stable technology, and form a good basis for a more refined, autonomic NMS framework due to its agent-based nature and implementation of a common data management structure.

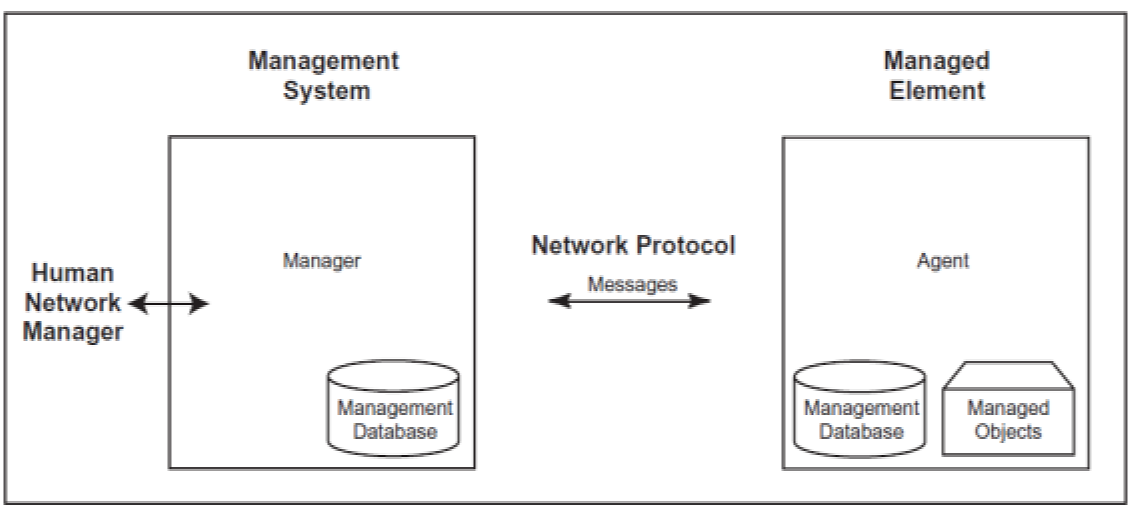

Figure 11. Basic SNMP manager/agent architecture (From Puff 2011)

While the 8th layer concept addresses the core requirements for autonomic computing, a more elaborate structure must be developed to incorporate more robust self-management functions. The use of an SNMP-based communication framework implies a centralized or strictly hierarchical operating model. Furthermore, while the concept of incorporating business rules into the standard OSI framework is a novel approach to a policy-driven framework, the MIB structure to monitor and enforce those policies will tend to resist a highly scalable and dynamic network topology (Potier and Qian 2011). A problem with using SNMP-based management architecture approaches in MANETs is the cost of maintaining a hierarchy to disseminate requests and collect replies in the face of node mobility. That cost is the introduction of additional overhead that increases energy consumption and decreases the available bandwidth (El brak et al. 2011). The core concepts of the 8th layer (self-management, agent-based management, and distributive NOC functionality) serve as a sound foundation for further development of an agent-based, policy-driven autonomic NMS. However, for a true 8th layer hypernode to emerge, NOC intelligence and functionality must be holistically distributed and dynamically updated for systems to become more coherently adaptive, resilient, and less reliant on human system administrators for network management tasks (Oros 2007).

2. Policy-Driven, Autonomic Network Architecture

The principle of a policy-driven, autonomic network management framework furthers the 8th layer hypernode model by introducing the core concepts of a self-management capability. Further defining those core concepts of self-management, there are four basic properties of elements that comprise an adaptive, autonomic system (Ayari et al. 2009):

1. Self-configuring: This property refers to the capacity of the systems to configure and reconfigure in accordance with high-level policies in changing environments. It involves the ability of both the new

component and the existing system to install, configure and integrate when a new component is introduced to a system. The component would be able to incorporate itself seamlessly, and the system would adapt itself to the component's presence. The end system could then efficiently make use of this component.

2. Self-healing: This property is the capacity of discovering and repairing potential problems to ensure that the system operates smoothly.

3. Self-optimizing: The objective of self-optimization is to enable efficient operation of the system even in unpredictable environments. An autonomic computing system will proactively seek opportunities to make themselves more efficient in performance and cost. For this, the system should be aware of its ideal performance, measure its current performance against the ideal, and have strategies for attempting improvements.

4. Self-protecting: Self-protection involves the ability to protect itself from cyber warfare techniques (e.g.,, malicious attacks and intrusions).

In an ideal autonomic system, autonomic elements exhibit all of these capabilities (Hadjiantonis and Pavlou 2009). In autonomic systems, autonomic elements are those elements that contain resources and contribute to the self-management process. An autonomic element is comprised of the following (Ayari et al. 2009):

1. A *monitor*, which is responsible for knowledge gathering

2. A *knowledge base*, which consists of a repository where policies and monitored information are stored

3. An "*analyze and plan*" component, which analyzes knowledge and constructs plans of actions

4. An *executor*, which reconfigures the system regarding to the output of, analyze, and plan processes.

These elements work together to constantly monitor knowledge of the node's external environment, construct plans based on analysis of that knowledge, and then execute those plans that best fit the overall objectives issued by the administrator. This cycle of self-management builds upon a simple closed loop system (Figure 12).

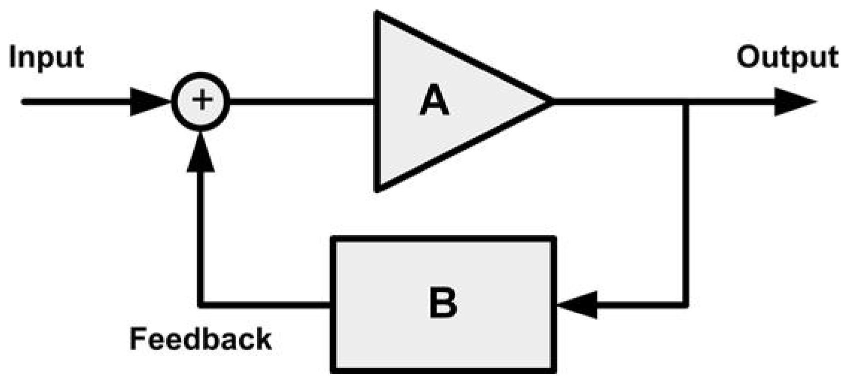

Figure 12. Closed Loop System (From Hadjiantonis and Pavlou 2009)

By using a system's output as feedback, a feedback loop allows the system to become more stable and adapt its actions to achieve desired output. This process forms an autonomic control loop (Ganek and Corbi 2003). Figure 13 illustrates the elements of an autonomic element coupled with an autonomic control loop that elaborates on the basic management process illustrated earlier in Figure 10.

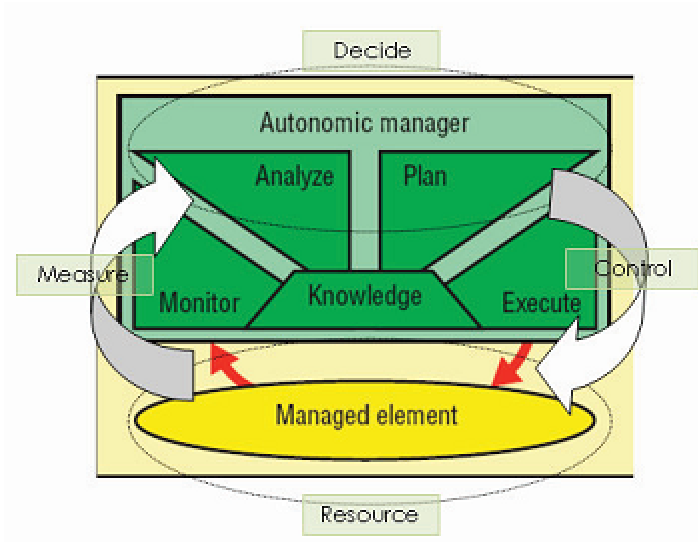

Figure 13. An Autonomic Control Loop (From Ayari et al. 2009)

a. Early Attempts at MANET NMS Design

Early efforts to design MANET NMS's focused on the monitor and execute aspects of autonomic elements, leaving out much of the analyze and plan aspect, as well as addressing the fundamental differences between static and ad hoc networks. The Ad hoc Network Management Protocol (ANMP) is an example of this early work. ANMP is an SNMP derived protocol designed essentially to transition the management paradigms of static wireline networks towards mobile ad hoc networks. The basic underlying model of ANMP involves clusters of managers and clients that form a hierarchical management framework (Figure 14). However, since it is SNMP-based, due to the size and highly dynamic topologies inherent in MANETs, it becomes infeasible to manage nodes using the conventional, centralized and hierarchical management approach of SNMP. Also, as a derivative of SNMP, ANMP also lacks the efficiency, reliability and robustness expected in a protocol for MANETs (Iskander and Younis 2008).

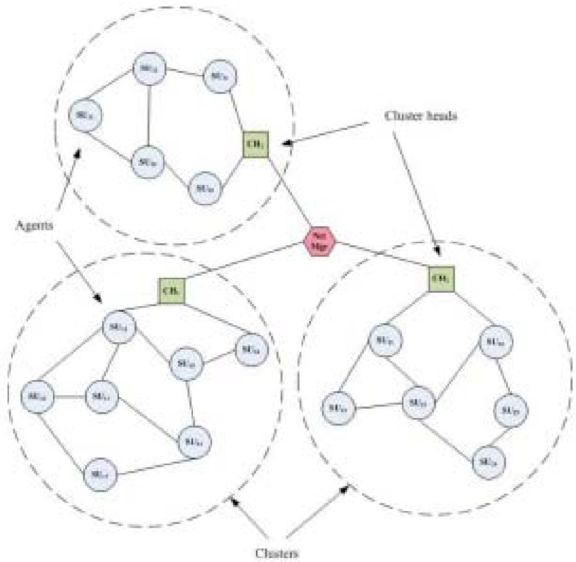

Figure 14. ANMP Cluster Network (From Potier and Qian 2011)

Following the lessons gained from early attempts such as ANMP, recent work has focused on policy-based, autonomic network management architectures (Hadjiantonis and Pavlou 2009). Two recent examples of an architecture that couples policy-based management and autonomic networking are the Autonomous Decentralized Management Architecture (ADMA) and Dynamic Re-addressing and Management for the Army (DRAMA).

b. ADMA Core Concepts

ADMA's proposed solution to distributive MANET management closely mimics the core 8th layer hypernode concept where each node contains some internal NOC capability that takes into account some high-level policies to make autonomic management decisions. In contrast to the 8th layer ADMA, does not implement an extension to the OSI stack as a means to implement and enforce policy. Instead, each node contains elements of an internal autonomous agent; those elements include (1) a Local Policy Decision Point (LPDP) that governs resource and node configuration, (2) a monitor that collects and stores local and external information, (3) a Policy Enforcement Point (PEP) that enforces LPDP decisions, and (4) a Local Policy Repository that stores policies locally in the node (Figure 15). Furthermore, ADMA defines four primary classes of policy: (1) Configuration (global base configuration settings), (2) Reconfiguration (policies that dictate actions in response to an event or threshold value), (3) Monitoring (specifying what information to monitor), and (4) Meta-policies (specifying characteristics of policies such as enabled/disabled or precedence) (Ayari et al. 2009). This is a more specified approach to policy that focuses on the agent itself compared to the 8th layer where the focus is on services provided to external network. The ADMA framework supports each element of the agent working independently and reduces overhead by focusing policy management at the node rather than over the network. This approach utilizes a highly decentralized management approach where every node is autonomously responsible for network management functions across the mesh. While more directly representative of a MANET topology, the highly decentralized focus of ADMA lacks the ability to support the broader network management functions needed in an EMO/ECO employment scenario (e.g., collaborative response to events that affect more than one node simultaneously, mechanisms to adjust global policies as an adaptation response to the environment).

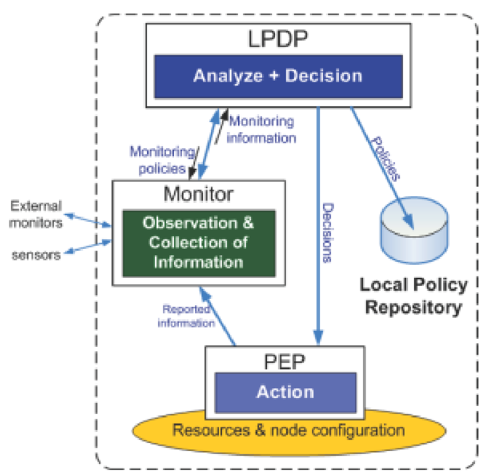

Figure 15. ADMA node architecture

c. *DRAMA Core Concepts*

While DRAMA also uses a distributed agent architecture, DRAMA employs a robust policy management organizational model. In DRAMA, the policy agents are distributed in a tree hierarchy that rapidly adapts to changes in the MANET topology (Figure 16). While ADMA approaches each agent as its own complete entity capable of every management function, DRAMA uses a role-based agent paradigm. As illustrated in figure 16, Local Policy Agents (LPAs) are the base elements of DRAMA instances. They are responsible for gathering network status data and managing networking elements locally. Domain Policy Agents (DPAs) are intermediate nodes in the tree hierarchy; they receive summarized reports from subordinate LPAs and manage local elements. DPAs report the combined status of their local elements and their subordinate reports to their respective masters, which could be other DPAs or the Global Policy Agent (GPA). At the top of the hierarchy is the GPA that receives reports from subordinates and forms the root of the tree. DRAMA includes provisions for dynamically adjusting roles and message store-and-forward capabilities. Combining the distributed agent model of ADMA with the dynamic role and topology configuration ability of DRAMA lends towards further development of the Marine Corps tactical MANET concept and an optimal operating model for an EMO/ECO NGC2 system.

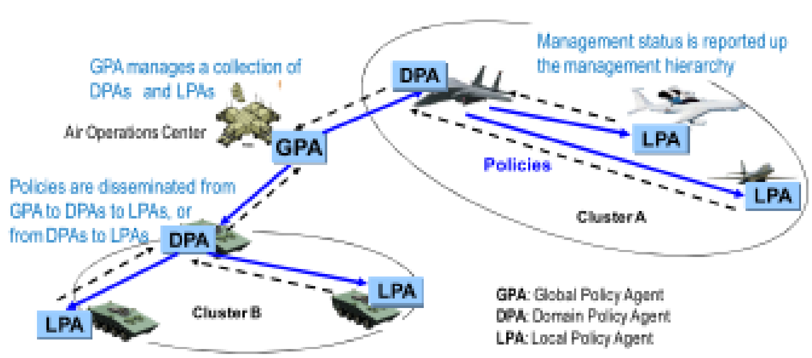

Figure 16. DRAMA Architecture (From Wolberg et al. 2011)

3. Developing a Contextual Self-Management Framework

Even though ADMA and DRAMA present excellent operating models for MANET management and provide for policy-driven networking, they do not address a contextual framework. As a critical element of enabling self-management, the Marine Corps must develop a contextual framework for evolving current network management capabilities towards more autonomic networks. While policy-based management concepts constitute a great portion of an NMS, policy-based management concepts address primarily only the *Planning* and *Plan and Execute* components of an autonomic system. Towards developing a complete autonomic system, the context-aware framework defines the Monitor and Analyze functions (Figure 13). Figure 17 elaborates on this and each function. Furthermore, the specification of policies and context, together with their interaction, form the essential knowledge element (Hadjiantonis 2012).

This knowledge element provides for a prominent feature of a next-generation NMS: the capability of the NMS to learn through experience and refine policy over time. By combining a policy-driven management concept with a context-aware framework, systems that autonomously refine and optimize the network begin to emerge. This ability for a network to emulate its human administrators is a critical element in the Marine Corps' NGC2 NMS vision. This will form a link between human cognition and machine computational abilities, and reflect the emerging symbiosis between a maneuver force and its constituent networks.

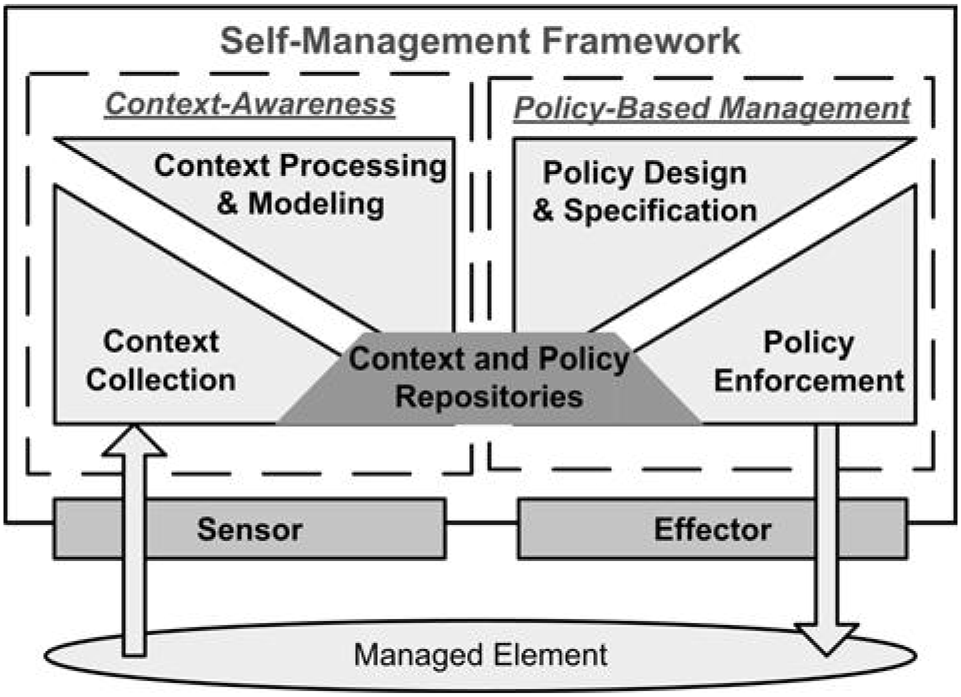

Figure 17. Mapping context-awareness and PBNM to an autonomic manager component (From Hadjiantonis 2012)

This evolutionary process emerges from enabling a context-aware capability across the MANET. To provide for this context-aware component in this self-management framework, the framework must first provide a context taxonomy that assists the structuring of a node's monitoring capability. By unifying a common taxonomy for MANETs, nodes have a common framework by which to share awareness across the network, and eventually share knowledge of the environment across the network, regardless of any node's specific physical location. Hadjiantonis (2012) describes taxonomy of context information that distinguishes persistence, fluidity, and nature (Figure 18). This taxonomy is general enough that it supports a large range of descriptors, but is exhaustive enough to provide a basis for context modeling and eventually policy enforcement. The Naval Postgraduate School has conducted research on defining ontologies within tactical networks (Hayes-Roth and Blais 2008) to help define contextual relationships. This ontology serves to provide a holistic worldview that is consumable by both human and machines, enabling the human operator to intuitively see the network from the combined perspective of the entire network.

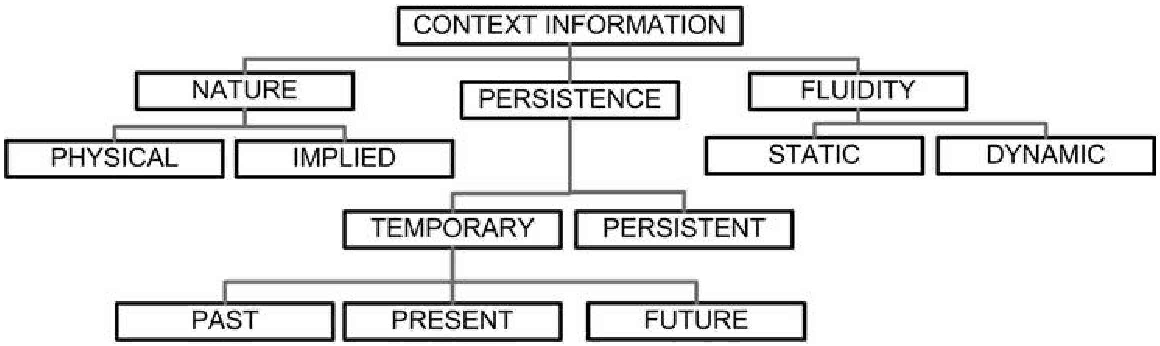

Figure 18. A Taxonomy of context information (From Hadjiantonis 2012)

After defining taxonomy for context information, next comes an examination of the framework for the storage and distribution of context information. The 8th layer hypernode concept provides a good working foundation for storage of this taxonomy and proposes a MIB-based specification for such context taxonomy (Bordetsky, Dolk, and Zolla 2004). Similar to SNMP MIB variables, contextual taxonomy can be stored as a MIB database, identifying contextual information within an Object Identifier (OID) tree. This approach works well in terms of contextual taxonomy because the taxonomy is not expected to change rapidly, and it remains relatively static and independent of the topology or scale of the network. The 8th layer conceptual framework furthermore describes a knowledge base as the primary mechanism for storing contextual taxonomy and policy within a cognitive network and would serve as the network's collective "memory" of contextual experiences (Bordetsky and Hayes-Roth 2009).

Again, as Hadjiantonis posited, the specification of policies and context, together with their interaction, form the essential knowledge element. Policies encapsulate high-level directives as well as low-level actions to achieve management objectives. Context modeling, on the other hand, provides a layered view of network conditions by collecting and combining simpler context to complex ones. Because this knowledge is a central component to the self-management cycle, it follows that this information must reside across all nodes. This distributed storage mechanism is critical in the case where a node is disconnected from the larger mesh. Hadjiantonis proposes a Distributed Policy Repository (DPR) as a means to extend the 8th layer knowledge base concept by employing a distributive storage and replication mechanism for both context and policy together. The DPR specification details a separate physical repository for policy and contextual information. The DPR framework distributes policy repositories across a cluster/hierarchy similar to the DRAMA policy distribution model where policy is stored globally equal to every node on the network and assumed persistent and global. In contrast, contextual information is assumed highly localized and temporal, only requiring temporary storage and only the information required for the inference of network-wide context is distributed (Hadjiantonis and Pavlou 2009).

In their research, Hadjiantonis and Pavlou propose a hypercluster organizational paradigm for context and policy information flows (Figure 19). This hypercluster structure is an instance of the hybrid operating model by incorporating a distributed management federation of one or more privileged nodes with extended capabilities (Hadjiantonis and Pavlou 2009). As nodes join or disassociate from the network, this distributed federation of managers can adjust and reorganize as needed. This model provides for a highly dynamic management structure that reduces redundancies in management information flows and can adapt for localized management to support the self-forming of meshes.

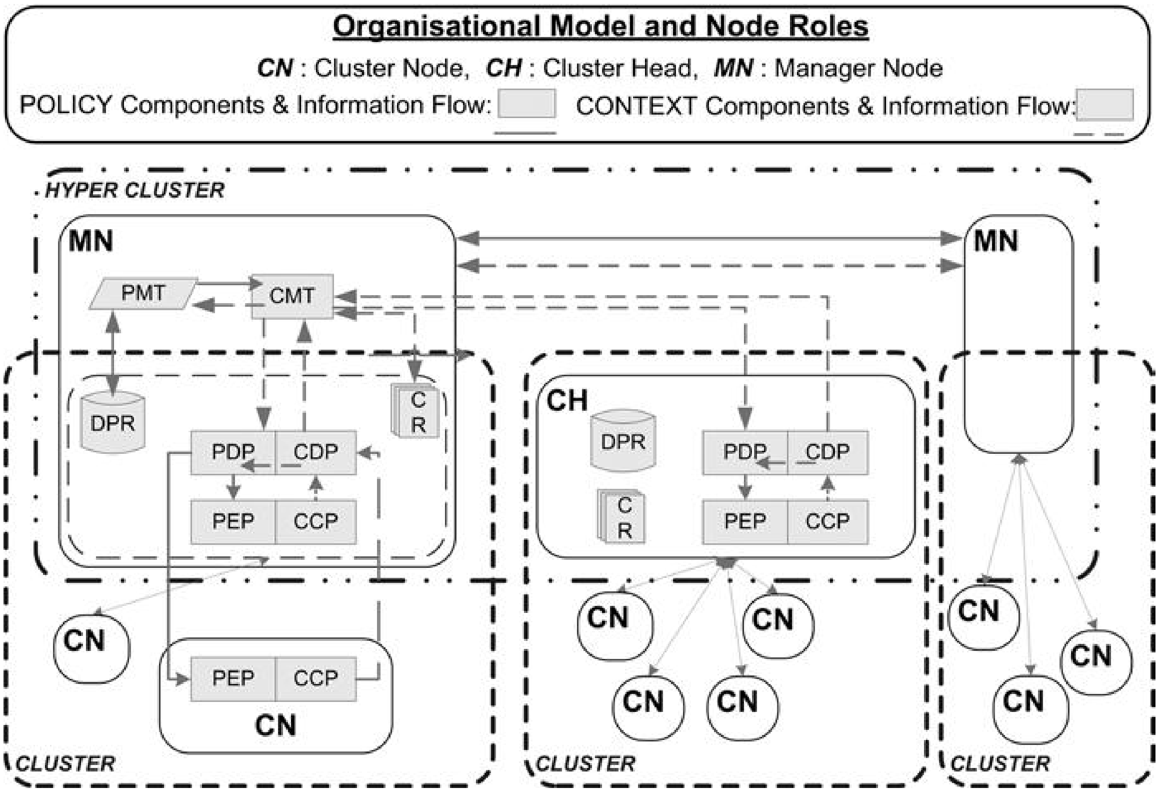

Figure 19. Illustrating the hybrid organizational model implementation of the components of context and policy information flow (From Hadjiantonis and Pavlou 2009)

In describing an autonomic system that is able to generate the interdependence envisioned by the distributed command and control model of EMO/ECO, this research has identified the fundamentals of this self-management framework:

- a distributive network management paradigm that focuses on network management from the bottom-up, vice a centralized top-down approach
- a policy-based network management framework that derives context from every node on the network as a trigger for executing policy decisions
- an autonomic network paradigm that leverages a PBNM framework for enabling self-management functionality

These elements taken together describe the framework for evolving a network management paradigm from centralized, operator-dependent NMS towards an autonomic operator-cooperative NMS. Without having a framework and mechanism for predictive and adaptive capabilities within a MANET NMS, the evolution from basic/managed networks to adaptive/autonomic networks will never occur. To meet this goal, this research thesis uses the frameworks described by ADMA, DRAMA, and other research on policy-based network management and extends them to include an agent-based predictive/adaptive reasoning component. The mobile agent represents an instance of what the 8th layer hypernode concept refers to an a node's internal NOC. The mobile agent in the case of tactical MANET NMS', refers to a common collection of logic and software that resides across all nodes that serves as the mediator between physical management of the node and the logical autonomic process that permeate the network.

III. AN AGENT-BASED AUTONOMIC C2 FRAMEWORK IN SUPPORT OF EMO/ECO

A. AGENT-BASED AUTONOMOUS NETWORKS IN TACTICAL MILITARY APPLICATIONS

Mobile agents have been proposed as a means to balance the burden of processing management data and decreasing traffic associated with management of ad hoc networks (Mishra and Sharma 2010). In that proposed framework, agents conceptually represent a human operator residing within the node itself. Just as human operators are able to perceive their environment and exist independently or collaboratively work together, mobile agents exhibit similar traits to their human counterparts. As autonomic collections of NMS programs and logic, agents represent a specific instance of that NMS intelligence. This enables an agent to either exist independent of the rest of the network or work collaboratively with other agents to perform collective execution of network management activities (Mishra and Sharma 2010). This employment scheme conceptually supports the bottom-up network management paradigm, where the strength of the network originates from the nodes (i.e., the availability of the network directly correlates to the presence of a node, the preponderance of network management activities originate from each node). The nodes contain the bulk of the network management capability and the means to allow the network to permeate down to every individual actor on the battlefield, whether it is a Marine, a HMMWV, or a weapon system.

To realize this employment scheme, it is imperative that every node correlate to an actor on the battlefield. One Limited Objective Experiment (LOE) conducted by MCWL concluded that it was not imperative for every Marine to carry a TW-230 device (Matkins 2010). This conclusion incorrectly understates the symbiosis potential for MANETs, and implies that MANET technologies are just a kind of voice radio that just happens to provide data features. For the purposes of the LOE, MCWL only examined the capability of the devices as simple extensions of network links and as a result, sold the potential capability short.

The previous chapter discussed how to extend the potential capability of symbiotic network/maneuver operations by introducing a conceptual framework for how to apply agent-based autonomic networks to support adaptive tactical operation's requirements. Furthermore, it discussed how predictive and adaptive capabilities precede a true autonomic system. Predictive modeling is critical to efficient management of tactical networks since things change so fast, the only way to keep up with those dynamics is to proactively manage rather than reactively manage. The inclusion of predictive elements to cognitive agents enables those agents to evolve beyond being a reactive element and become proactive actors in their environment.

B. MECHANISMS FOR DRIVING ADAPTIVE REASONING IN AUTONOMIC NETWORKS

Essential to developing a predictive/adaptive capability begins by developing a framework for the feedback loop mechanism. The 8th layer concept provides a vision for how to extrapolate a procedural model of the basic autonomic feedback loop (Figure 20). In the 8th layer, each hypernode would be able to evaluate its own controllable variables and attempt to optimize its own sub network, either independently, or in concert with adjacent hypernodes (Bordetsky and Hayes-Roth 2009). This would form a feedback loop, as changes (either as a function of the environment itself or actions previously taken by the hypernodes) are made to the shared network model.

As the feedback loop is heavily dependent upon the ability to process contextual information, it follows that there must be some mechanism for enabling context awareness at every node, and the ability to share that context across the MANET. This research examines three prominent features of storing, communicating, and deriving meaning from contextual information: a knowledge base, the concept of *Valued Information at the Right Time* (VIRT), and Case-Based Reasoning (CBR) mechanisms.

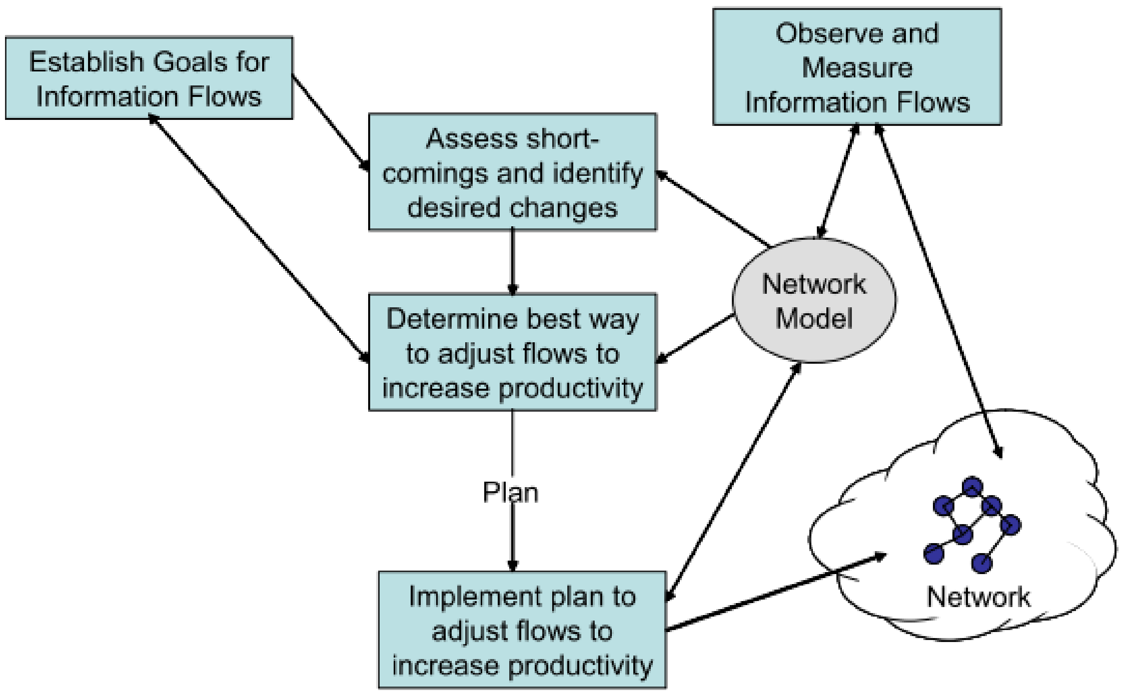

Figure 20. Generalized adaptation model for hypernodes in autonomic networks (From Bordetsky 2009)

1. Knowledge Base

As mentioned earlier, the knowledge element of the autonomic system serves as the central element around which the entire feedback loop revolves. From the monitoring element, through the context-awareness mechanisms, and through the policy resolution and enforcement mechanisms, the knowledge element drives every function. As such, the knowledge element serves as the base for elements of every portion of the cycle. The knowledge base represents a repository for the historical shared awareness in terms of condition/action couplings. These couplings come from a combination of either a priori (in the case of experiencing previously known conditions) or a posteriori (in the case of experiencing new conditions) contextual information and resulting policy actions. These couplings become more elaborate and descriptive as more scenarios are added to the knowledge base, and more refined as sense-analyze-adapt scenarios are also added to the knowledge base. Hadjiantonis and Pavlou (2009) described the contextual framework for this kind of knowledge base in their DPR specification (Figure 21). The DPR framework also addresses the fact that as the number of policies increase, there exists the likelihood that policies will come into conflict due to either a specification error (e.g., two policies define contradicting actions for the same event) or because of application-specific restraints (e.g., the prescribed policy action conflicts with the mechanical parameters of the device) (Hadjiantonis and Pavlou 2009). To address these conflicts, DPR proposes metapolicies (e.g., hierarchical precedence, user-defined preferences, if-then-else conditionals) that can recognize these policy conflicts and serve as mediators.

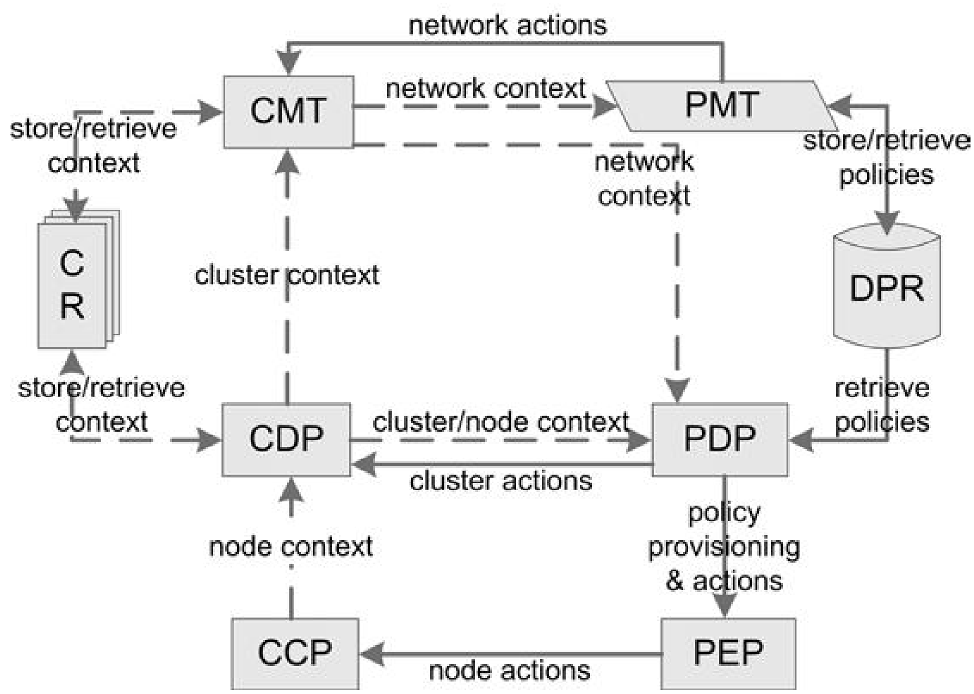

Figure 21. Policy-based and context-aware components and interactions within the DPR framework (From Hadjiantonis and Pavlou 2009)

The DPR framework specifies that nodes only share contextual information as needed, and distribute policy globally, regardless of context of the node. However, since this research posits that the network management function emerges from a holistic, shared worldview from *every* node in the network, it is critical to define a framework that supports sharing meaningful contextual information from everywhere in the MANET. Extending the DPR framework, this research introduces the VIRT concept as a means to develop a shared worldview through exchanges of meaningful contextual information and concretely define what *meaningful* means in the context of network management activities across the mesh.

2. Semantic Information Models and Valued Information at the Right Time (VIRT)

There are two significant constraints that affect network management of complex networks such as MANETs, limited bandwidth across the mesh, and limited time for operators to process and act on information. It makes an enormous difference to assure that only relevant information is delivered in a timely manner to each recipient. Hence, the network should become aware of the dynamic information requirements of each recipient. The network can then assure its limited resources are allocated first to assuring such valuable information reaches its intended recipients (Bordetsky and Hayes-Roth 2009).

The VIRT concept addresses this inherent constraint of limited bandwidth and timeliness, and acknowledges that just providing more information to operators across the network does not necessarily correlate to a greater shared awareness nor improved performance at attaining goals. VIRT's approach to reduce "information glut" is to focus the entire network on the recipient's perception of valued information, and cause the network to filter and prioritize appropriately (Hayes-Roth 2006). Studies on the application of VIRT observed that by using the VIRT framework, there is a five orders of magnitude reduction in information volume across a network (for more details see Bordetsky and Hayes-Roth 2009).

This recipient-centric approach is similar to the relationship between the CCIR and PBNM architectures. As discussed earlier, CCIR are a component of those mission-type orders that preceded the establishment of policy-based decision-making. The VIRT concept describes a modified control loop, where only information that is valuable to the consumer is fed back into the loop (Figure 22). The VIRT concept refers to this valuable information as a *Condition of Interest* (COI).

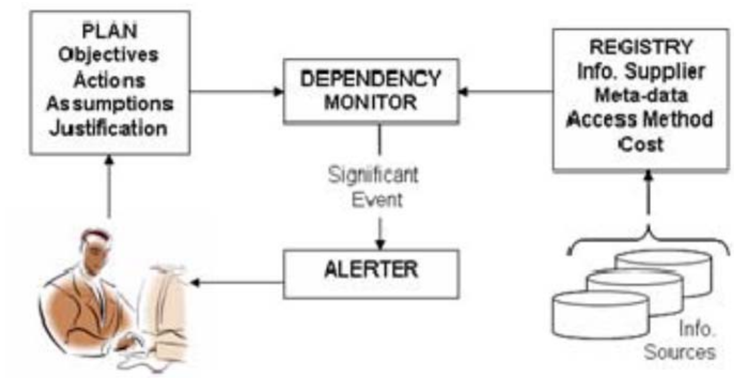

Figure 22. A basic architecture of the VIRT concept (From Hayes-Roth 2006)

Extending this concept builds towards a framework for how an autonomic system can communicate contextual information and policy decisions across the network. In the logic of the monitoring system of each autonomic hypernode lies a dependency monitor that is fed by a VIRT registry. This registry defines COIs for nodes across the network. This is the third aspect of the previously discussed knowledge base (see chapter 3, section b.1). Combined with context and policy repositories, a VIRT repository contains metadata that defines how the coupling of context with policy is turned into action. Essentially, these COIs serve as trigger mechanisms for enacting policy enforcement across the MANET. Not only do these COIs serve as a trigger mechanism for policy action, but also a means to develop a more meaningful shared world model by only sharing critical network COIs such as (Oros 2007):

- The current/expected/forecast tactical network topology
- Identification and location of critical C2 nodes
- Alerts when any critical C2 node have impending power/hardware/software failures
- Alerts when peer node transmission packet loss exceeds a certain threshold
- Available CPU processing time of any adjacent node
- Alerts when a node approaches its communication/reception threshold (e.g.,, bandwidth/RSSI/Signal Correlation/SNR, etc.)

Conditions of Interest such as these are representative of a semantic model that both human and computer operators can interpret. Defining this semantic model provides a way to bridge the gap between machine and human cognition. This lends towards more intuitive network management systems because common languages (or common translations between human language and computer language) are useful to developing a more complete situational awareness picture and more advanced policy interactions. Research at NPS has explored development of such a semantic object model (Figure 23) for the 8th Layer hypernode concept (Oros 2007). While still developmental, this model serves as a basis for the structure of a VIRT COI repository.

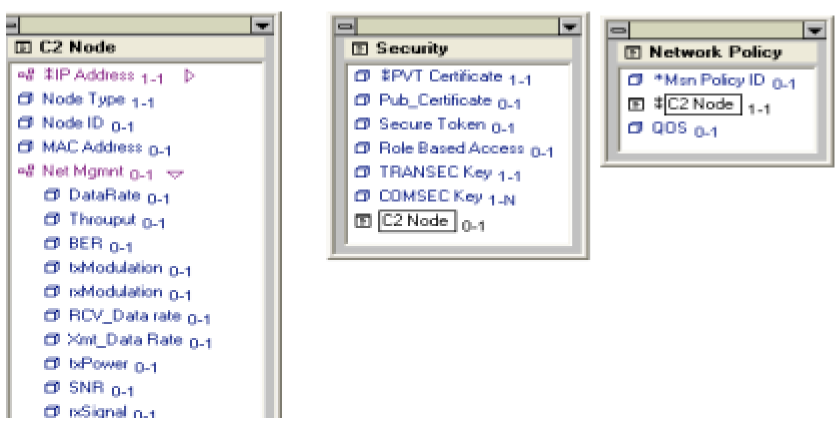

Figure 23. An 8th Layer network management semantic object model (From Oros 2007)

3. Case-Based Reasoning (CBR)

Case-Based Reasoning is an automated decision support system concept that uses the knowledge gained from previous experiences to propose and refine solutions to new problems. As a decision-support concept, CBR provides a conceptual framework for how an agent processes policy and context information to develop knowledge, and uses that knowledge as a basis for adaptive reasoning. The CBR architecture includes the case library where previous situations and their solutions are stored. A query of the case library, based on a discovered anomaly, reveals if any matching solutions already exists. In the case of a "never before" detected situation, the closest match from the search is adapted to the current situation. The case library is the updated with the problem and its solution once it is resolved (Puff 2011). This retrieve, reuse, revise, and retrain cycle is illustrated in figure 24.

Besides using COIs as a means to derive meaning and support decision making from a context-aware autonomic system, Case-Based Reasoning can also be used as a mechanism to store the collective memory of the network's experiences in a knowledge base. Through a CBR decision-making cycle, the context/policy/VIRT repositories combine to create a knowledge base that serves as a memory of the collective mesh node's experiences.

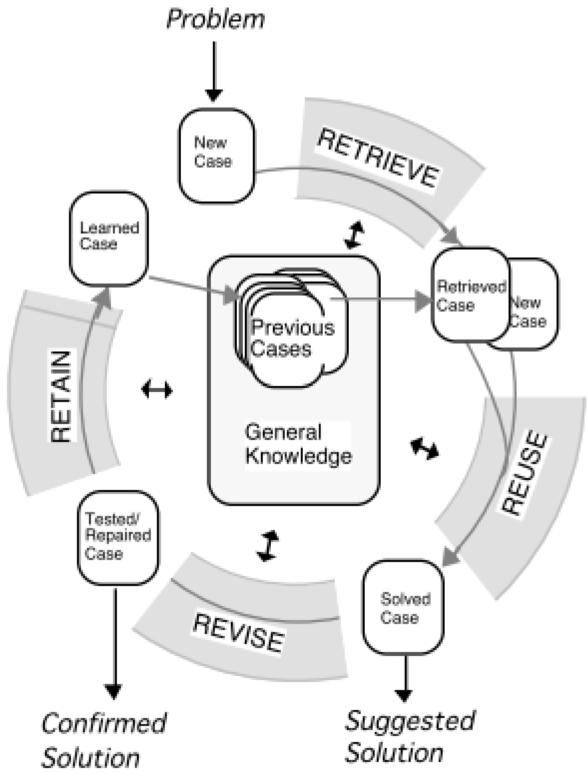

Figure 24. CBR Cycle (From Aamodt and Plaza 1994)

Not only does a CBR approach help to solidify a holistic worldview across the network, but it also serves as a driving mechanism for VIRT activities. In the CBR cycle, VIRT COIs are compared to the case library in the retrieve and reuse phases, but then, though the revise and retrain phases, VIRT revises COIs across the network and communicates any relevant actions that were taken by the node. The result of combining CBR and VIRT further reduces the load over the network (since less bandwidth is needed to communicate management functions) and increases the speed in analysis of policy enforcement (since policy enforcement relies on event/action correlations).

C. MODELING AND SIMULATION FOR ADAPTIVE MANAGEMENT

Just as this thesis research considers that MANET agents emulate individual human agents and their capacity for reason, it follows that in order to properly represent an agent's environment, an examination of how the relationships between agent's builds towards a somewhat sociological aspect must take place. Recent research explores how the dynamic behaviors of MANET agents arise from interactions between agents and their environment (Ntuen and Kim 2011). In Ntuen and Kim's research (2011), they propose a cognitive model that approaches MANET as a cognitive social system of intelligent behaviors between MANET agents (Figure 25). Their model predicts network metrics such as vulnerability, resiliency, and reliability by observing the cognitive agent interactions across the MANET and extrapolating meaning from those interactions.

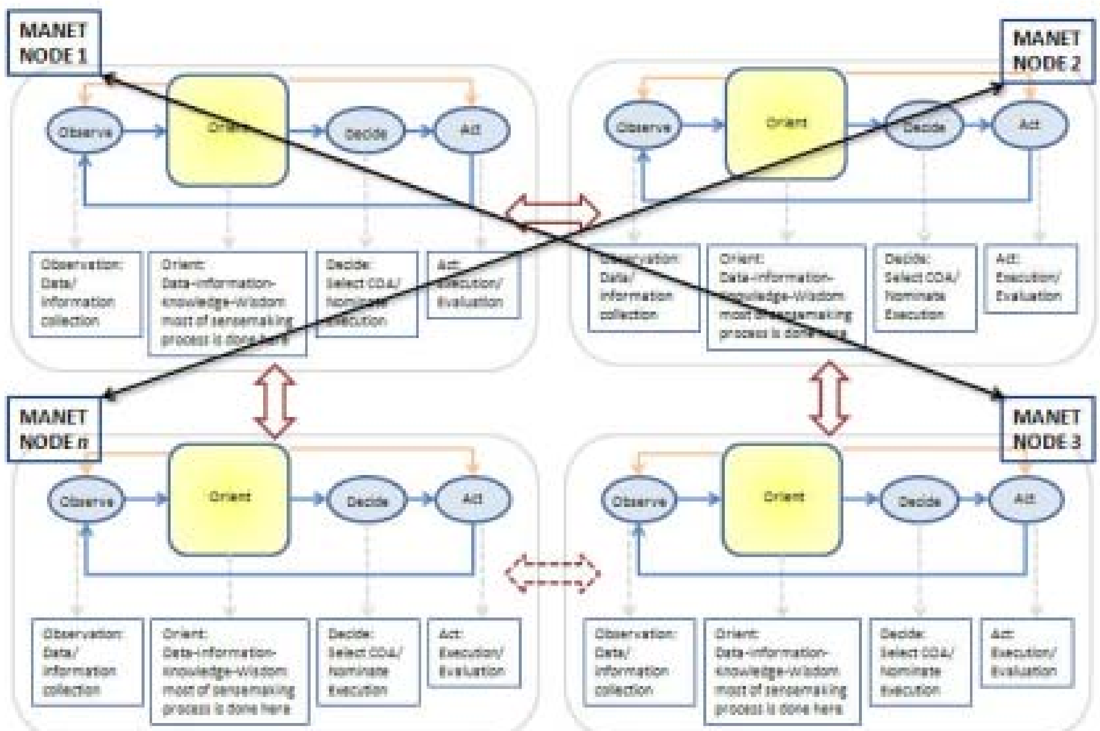

Figure 25. Cognitive interactions between autonomic agents (From Ntuen and Kim 2011)

Here to fore, this thesis focused on the comparison of autonomic agents to their individual human correlates in terms of management functions; however, in the broader physical aspect, MANETs more closely represent swarms of entities, similar to the sociological approach of Ntuen and Kim. Each element in the mesh exists independent of the rest of the network, but the strength of the MANET comes from the cumulative interactions of every node. Assuming a fully autonomic network, these interactions lead to emergent intelligent behavior that reflects the swarm's collective strengths (e.g., cumulative RF gain from clustering, increasing network availability as the mesh becomes more dense) and vulnerabilities (e.g., increasing management complexity as the mesh grows) as the network seeks to adapt itself to its environment.

Because of this emergent behavior combined with the inherent MANET properties of self-forming, self-organizing, and self-administering, research into Swarm Intelligence (SI) algorithms has become a leading field of study in MANET modeling and management (see Sharvani and Rangaswamy 2011; Y. Cho et al. 2010; Konak, Dengiz, and Smith 2011; Hunjet, Coyle, and Sorell 2010). Swarm intelligence describes the behavior of agents that work in a decentralized manner with no infrastructure controlling them. This is model makes the movement of nodes in a MANET analogous to a swarm of birds or fish moving collectively. For this reason, SI attempts to describe the collective behavior of decentralized self-organized systems as a means of developing predictive and adaptive management solutions. Using the conceptual framework of Swarm Intelligence, those SI algorithms serve as the basis for predictive and adaptive features within a MANET management system. Because the general aim of SI adaptation algorithms seeks to maintain an optimally connected mesh, it naturally follows that the two prominent elements to model in any MANET are node mobility and link availability.

1. Modeling Node Mobility and Link Availability

As a leading class of SI algorithms, Particle Swarm Optimization (PSO) is a popular method for MANET predictive/adaptive network management (Sharvani and Rangaswamy 2011; Y. Cho et al. 2010; Konak, Dengiz, and Smith 2011; Hunjet, Coyle, and Sorell 2010). PSO is a population-based meta-heuristic that emulates the social behavior of species that live in the form of swarms in nature. In PSO, the aim of particles is to search for the optimal point in a continuous search space as they constantly move from one point to another according to their velocities (Konak, Dengiz, and Smith 2011).

Use of PSO algorithms in an agent-based system will facilitate development of a shared worldview as each node works cooperatively to optimize the topology of the mesh. In order to do so, every node shares specifics such as its relative position to neighboring nodes, relative velocities, number of concurrent links to neighboring nodes, and transmission power. Recent implementations of PSO algorithms are useful to employment schemes inherent within the EMO/ECO concept.

Swarm optimization algorithms have been proposed to control the autonomous relocation of nodes in response to anticipated link loss in a MANET (Hunjet, Coyle, and Sorell 2010; Sharvani and Rangaswamy 2011). Other research has proposed methods on how to determine optimal node location in a MANET based on PSO clustering algorithms (Y. Cho et al. 2010). While these node mobility models serve to ensure an optimal mesh topology, predicting the quality of the links themselves will form a much more holistic model of link quality and availability, and can serve to develop greater predictive capabilities throughout the network. A novel approach to determining link quality and availability is to combine the generalized picture of PSO with link-specific attributes. This approach models the network as a mechanical system with springs and a viscous damper. Specifically, this approach models the communication energy cost as an artificial potential energy stored in springs, and nodes as objects with unit mass, moving according to the artificial force field, i.e.,, the negative gradient of an artificial potential function (S. Cho 2009). Essentially, this model attempts to relate a specific link quality as the change in tensile force and potential energy of a mechanical spring within some fluid (Figure 26).

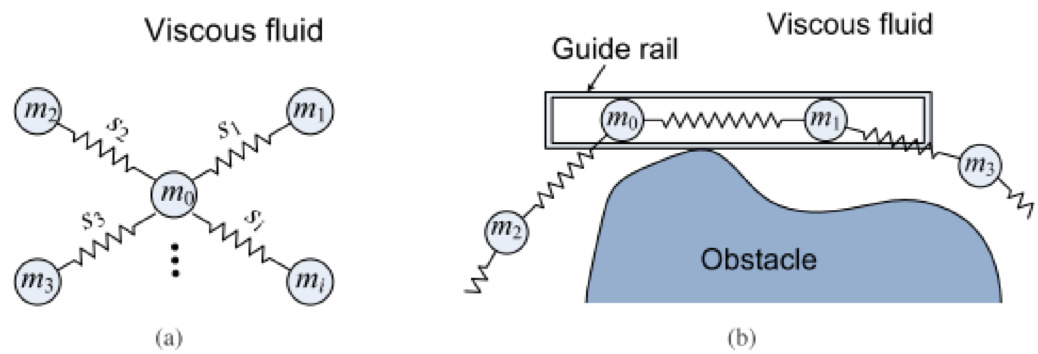

Figure 26. MANET structure modeled as a mechanical system in a viscous fluid: (a) connection with spring elements; and (b) connection with spring elements with a guide rail in contact with an obstacle (From S. Cho 2009)

By combining the modeling aspects of both node mobility and link availability, a network planner can begin to anticipate changes to the network, or effectively plan the SoM with the network in mind. This is especially useful because a planner can determine the optimal location to place nodes either prior to, or during tactical operations. These methods, when taken together, have powerful implications for the implementation of a next-generation C2 system for the Marine Corps. Some examples of this are:

- Nodes autonomously re-tasking UAV's to cover gaps in RF coverage
- Modeling node topologies and the affect changes to that topology have on the network
- Recognizing errant node movement outside of normal parameters as to infer alterations to the plan of attack (e.g., unplanned enemy contact, broken convoy vehicles en route)
- Running simulations before conducting operations to determine gaps in the network throughout a proposed course of action

These examples all support a COA development that takes into account network availability and quality as a central planning aspect in combat operations. The systems that support this next generation command and control paradigm must be able to intuitively communicate the relationships between nodes as well as those predictive elements that are crucial to preempting link loss or reduced fidelity across the network.

IV. USE-CASE SCENARIO DEVELOPMENT AND INTERFACE DEVELOPMENT CONSIDERATIONS

This thesis identified several key underlying mechanisms that drive adaptive reasoning for an agent-based, policy-driven command and control system: (1) the VIRT concept, (2) a knowledge base, and (3) Case-Based reasoning. Combined, these elements enable a shared contextual awareness across the network that allows intelligent nodes to coordinate activities, ultimately resulting in enhanced network availability and performance. To develop this capability, this thesis studies how these elements are interlinked, and explores their respective functions within the agent-based PBNM framework. This research uses observations and lessons learned from the Combined Warrior Interoperability Exercise 2012 (CWIX) and the Joint Interagency Field Exploration 2012 Experiments (JIFX). Both sets of experimentation used TrellisWare devices as the primary MANET platform from which all subjective experimental observations were made. In both experiments, the TrellisWare platform provided voice/data services at the tactical level, emulating either fire team-sized, or individual operator elements.

A. COMBINED WARRIOR INTEROPERABILITY EXERCISE (CWIX)

The CWIX program focuses on interoperability among NATO C4 systems and provides a venue for experimental system testing and evaluation. The CWIX exercise uses a testbed environment from ongoing Maritime Interdiction Operations (MIO) experimentation led by NPS's Center for Network Innovation and Experimentation (CENETIX). For NPS, the focus of CWIX 2012 was the examination of information flows associated with Position Location Information (PLI) management. The TrellisWare devices supported an information management architecture for disseminating PLI data though a tactical ad hoc mesh network that integrated boarding teams with higher-level command centers and agencies (Bordetsky 2012). CWIX 2012 was conducted between 4-18 June 2012. It contained three distinct phases, each reflecting different use-case scenarios for how mobile ad hoc mesh networks would support information sharing for various types of MIO operations.

Phase One of the exercise deployed the TrellisWare devices aboard a passenger ferry from Karlskrona, Sweden to Gdynia, Poland. The contact team operating the TW-230s and simulated a special MIO boarding team capable of detecting Chemical, Biological, Radiological, and Nuclear (CBRN) materials on a suspect vessel. The team swept the vessel for notional CBRN materials, and sent text reports and images back to higher headquarters in Bydgoszcz, Poland via a portable satellite communications (SATCOM) terminal operated by the boarding team officer.

Phase Two involved tracking PLI information from the port at Gdynia to Bydgoszcz. Three vehicles simulated a tracking scenario where nodes transmitted a continuous stream of PLI data between the vehicles and to higher headquarters via the portable SATCOM terminal from within one of the vehicles.

Phase Three deployed the TW-230s in a Maritime Interdiction Operation in Souda Bay, Crete. Operators deployed the TW-230s aboard security patrol boats to relay PLI and provide real-time video streaming and web services to all operators supporting the MIO.

1. Examining Information Flows Within, and Across Networks

In each phase of the experiment, the TW-230s provided a platform to demonstrate how the flow of information between different C2 systems performs depending on the needs of the operator and demonstrated how the application load across systems ultimately affected an operator's ability to perform his or her function. In Phase One, the primary information flow from the operator consisted mostly of unidirectional transfer of data gathered aboard the vessel to a command post in Bydgoszcz. Little information back to the operator was required, as the operator's mission only required sending products (e.g.,, pictures and textual data) back to a distant command center that would provide analysis and distribution of the information. In this case, the information flow was primarily one-way and illustrated the simplest information flow for tactical networks. This configuration required no specific information flows from higher echelons and reflected a fixed adaptation loop with a relatively static operating environment and information flows. The agents in this case, would experience changes in PLI, and adapt network configuration metrics to maximize upload speed. A knowledge base in this case would need to use a priori experiences from previous boarding events to reflect the environmental constraints and restraints inherent in a physically compact environment (i.e., stairwells, berthing corridors, compartments) to maximize network availability throughout the vessel.

The VIRT approach is appropriate in this case as a means to ensure minimal traffic across the network, thereby allowing more available throughput for large file transfers. The communications planner could implement a VIRT configuration where the TW-230's only transmit triangulated PLI data when in motion, instead of when static. This would ensure that the overhead associated with tracking operators throughout the vessel would not impede bandwidth when the operator was tethered to a computer and sending products back to headquarters. The quality of information flows in this case were tied to an adaptation loop that considered if the operator was in motion or not, and adapted network configuration traffic patterns as a result. Rules from this use-case scenario could be adapted to Marine Corps operations: in the case when the system detects the presence of a large file transfer event, to maximize the throughput for sending the file reliably and quickly, a shift to only transmitting only moving PLI data could temporarily go into effect.

In Phase Two, the focus of effort for information sharing was sending reliable and accurate PLI data from the vehicles to a command center in Bydgoszcz. The PLI data did not depend on operator action; the nodes autonomously generated and relayed PLI data. In this case, the PLI data represented rapid movement of vehicles across a large geographic region. As such, the absolute accuracy was not critical to operators in Bydgoszcz who only needed PLI accuracy to within several hundred meters to reliably track vehicle movement across Poland.

This use-case represents another scenario where an application specific knowledge base, VIRT, and CBR concepts used cooperatively would efficiently communicate relevant PLI information to command center operators. The lesson learned from this phase was that situational awareness metrics change according to the general scheme of maneuver. While it would be relevant to have deck-by-deck PLI while onboard a ship, command center operators only need broad PLI for vehicle-borne movement (~5km fidelity) as PLI served as a general reference indicator across a large geographic region. Again, in this use-case scenario, the agents must be able to not only see the lower level of maintain the network, but be involved in maximizing the network for specific data flows that are relevant to the scheme of maneuver.

By providing a C2 system with too much granularity, operators can be overwhelmed by information that does not add value to the operation. For example, when vehicles were in movement within an urban environment, too much PLI data obscured the general route that the target and chase vehicles were taking (Figure 27). In this case, an agent could have a general awareness of the mission and use application specific knowledge base parameters, CBR, and VIRT to determine transmission criteria (e.g.,, send PLI either every 5 minutes or every 5 km of movement). This would serve to limit the frequency of PLI updates to the system, thereby reducing visual glut in the PLI tracking system at the command center.

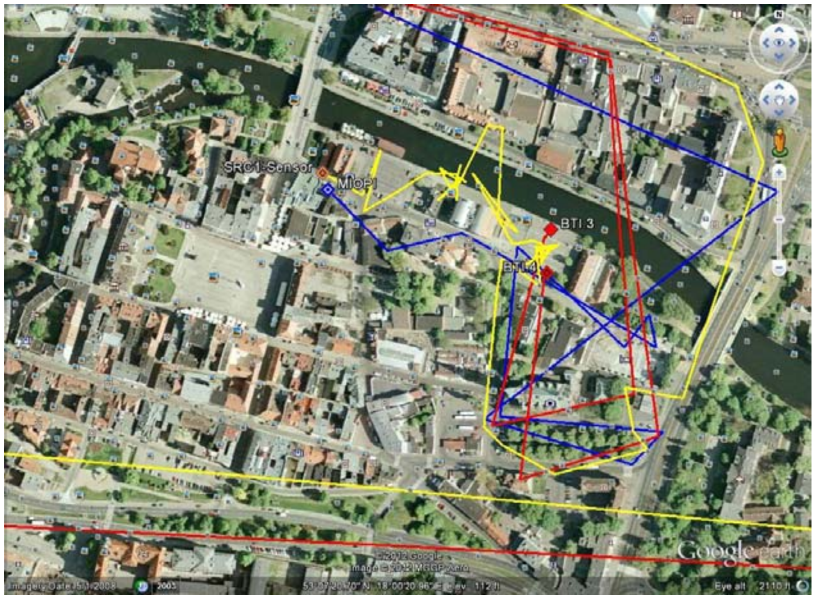

Figure 27. Example of trace PLI data clutter (From Bordetsky 2012)

Phase Three combined both application streams and PLI tracking into a simulated containment and boarding scenario. Patrol vessels contained a suspect vessel entering Souda Bay and conduct boarding activities to search for illicit materials and vet suspects against an anti-terrorism database. This scheme of maneuver required access to data services as well as transmitting real-time video and PLI information to higher headquarters. Due to the nature of the activity, reliable and ample throughput was required to successfully conduct operations without delay or error. Operators on the boarding teams needed rapid access to a database that was hosted at a facility not in the same geographic region, and command center operators needed uninterrupted access to the PLI and video feeds to adequately provide oversight and control of the operation. This two-way information flow represented a vigorous use-case scenario similar to most network activities expected within the EMO/ECO employment concept. This use-case, along with the others from CWIX, further supported the need to expand the knowledge base and CBR concept to include application specific adaptation loops. The knowledge base and CBR needed to address not only the health of the network, but the quality of application data across the network.

2. Knowledge Base, VIRT, and CBR Considerations

The lessons learned from CWIX proved that (1) the operator role is a prominent element in the design of autonomic management for information flows throughout a network, (2) that application flows must reach down to the individual node, and (3) every node is involved in the creation and dissemination of information—not just maintaining the mesh. This extends the basic premise of VIRT and supports the validity of incorporating VIRT in the development of EMO/ECO command and control concepts. This emphasis on relating the human element as a driver of information flow has a few implications for design considerations for a knowledge base and case-based reasoning mechanisms.

Further expanding the basic DPR framework described by Hadjiantonis and Pavlou (2009), the VIRT COI repository (as part of a distributed knowledge base) would integrate human/agent pairings with a generalized set of pre-defined policies reflecting mission objectives. By defining COIs to reflect mission priorities for each human/agent paring, a CBR decision-making cycle can prioritize application-specific traffic as the mission requirements dictate. Taking the CWIX experimentation as an example, using a VIRT/CBR framework, a MANET agent can determine when real-time video should receive priority for bandwidth, managing not only the quality of network itself, but managing application load across the network to maximize the availability and quality of the video. In concert, agents across the network could ensure that the video stream finds the optimal path to reach intended recipients, with a pre-determined desired level of clarity and fidelity.

Designing knowledge base parameters to include aspects relating to application load is an enhancing element to the basic underlying autonomic processes this thesis has discussed. Inclusion of these contextual parameters is critical when considering the quality and availability of the services those applications provide to the operator. For this reason, it is not enough that the autonomic agents work to increase the quality of the network; they must have elements that enhance the quality of services across that network. In his research, Puff (2011) described a similar mechanism, using SNMP MIB variables to describe qualitative metrics such as node status or network status as surrogates for inferring quality of the network, but he did not include variables describing services over the network.

This research proposes the use of a metadata taxonomy similar to Oros' (2007) research on semantic modeling and implementation of VIRT architectures for tactical operations (Oros 2007). This metadata would provide further context to application streams, identifying not only the type of traffic, but the content as well. This approach would support a publish/subscribe VIRT mechanism where operators would post subscription requests to streams of information that are valuable to them and the agents would only send (or send with priority) those information streams only as required. Using the phase three video stream scenario as an example, the node would announce a video feed service over the network. It would also provide context to the video stream by including metadata such as activity (e.g.,, aboard target vessel), originator (e.g.,, vehicle or helmet camera), or quality (e.g.,, optimized for mobile devices). Research at NPS describes this metadata as an extension of the SNMP MIB format (Gateau 2007). Figure 28 illustrates some potential MIB variables that supports publish/subscribe VIRT mechanisms. This kind of metadata allows nodes to intelligently prioritize and direct application streams as human operators need them. This has the effect of not only reducing traffic over the network, but ensuring that operators only receive relevant information as defined by their COIs.

Name	Syntax	Access	Description	OID
servIndex	INTEGER	read-only	A unique value for each service.	proServEntry 1
servName	DisplayString	read-only	A descriptive name of the service provided.	proServEntry 2
servReference	DisplayString	read-only	A unique reference for this service.	proServEntry 3
servDescr	DisplayString	read-only	A free-text description of this service. In the absence of other metadata, this description should be as complete as possible to allow other users to make decisions about the use of this service.	proServEntry 4
servIsMachine	BOOLEAN	read-only	TRUE if this service is automated.	proServEntry 5
servIsAvail	BOOLEAN	read-only	TRUE if this service is currently available. Additionally, a myServDown or myServUp trap should be sent to appropriate users when the Avail status changes.	proServEntry 6
servUrl	DisplayString	read-only	The Uniform Resource Locator where the service may be accessed.	proServEntry 7

Figure 28. Provided Services Metadata Table (From Gateau 2007)

B. JOINT INTERAGENCY FIELD EXPLORATION (JIFX)

The Naval Postgraduate School hosted a Joint Describing Interagency Field Exploration (JIFX) event 13-17 August 2012 at Camp Roberts, California. The JIFX event included science and technology representatives from each of the Unified Combatant Commands (COCOMs), Department of Homeland Security (DHS), and representatives from various academic and industry organizations. The focus of this event was to explore the potential of novel and emerging technological capabilities for the COCOMs and DHS, and how to integrate those technologies into evolving DoD/DHS capability needs (Allen 2012).

As part of the NPS experimentation team, personnel from NPS, Drexel University, and the Naval Research Lab deployed a fireteam-sized element[2] of four TW-230 radios to Camp Roberts. The purpose of this experimentation for NPS was to conduct initial field-testing of a prototype graphical user interface

[2] USMC fireteams are the smallest infantry element consisting of four Marines: a team leader, rifleman, automatic rifleman, and assistant automatic rifleman

(GUI) for representing real-time network quality in a heat map interface. Development of this GUI is in direct support to further development of the MCWL NMS-TM project as it enables an operator to intuitively grasp the strength and gaps of the network as a graphical overlay on real-time PLI data points and adjust network topology accordingly. Experiments conducted at JIFX contributed to refining the underlying algorithms used to develop the heat map overlay, and to conduct a proof-of-concept for the interface.

1. Refining Predictive Capabilities and Developing Intuitive User Interfaces

Expanding upon the initial design elements described by previous research at NPS (Puff 2011), the Naval Postgraduate School has focused on development of the prototype heat map application by examining network availability and quality as a function of the Signal-to-Noise Ratio (SNR) between subject nodes within a generic foliage RF propagation model. The heat map design is based on SNR as a sole indicator of network performance--this was an explicit design choice. NPS has hypothesized that SNR most directly correlates RF and network quality following the assumption is that higher SNR values will directly correlate to higher qualitative network assessments (Bourakov 2012). During JIFX, NPS performed field trials to refine the correlations between SNR and network quality and to provide a real-world demonstration of the real-time GUI concept (Figure 29). The design of the heat map is not limited to SNR only. As development continues, NPS expects to incorporate other metrics in its multivariate analysis (e.g.,, hop count and power output).

The deployment of the heat map prototype at JIFX demonstrates the knowledge base development concepts discussed within this thesis (see Chapter 3, section b.1). As more data gained from use-cases discovers emergent relationships between variables, the knowledge base will enrich the correlation between those key network metrics (e.g.,, SNR, hop count, and power output) and provide greater fidelity in the graphical interface. This feature of shared knowledge enriched by the collective experience of the network serves to illustrate how an autonomic network will tend towards systems that possess a holistic view of the network and intuitively communicate the relationship between nodes on the network.

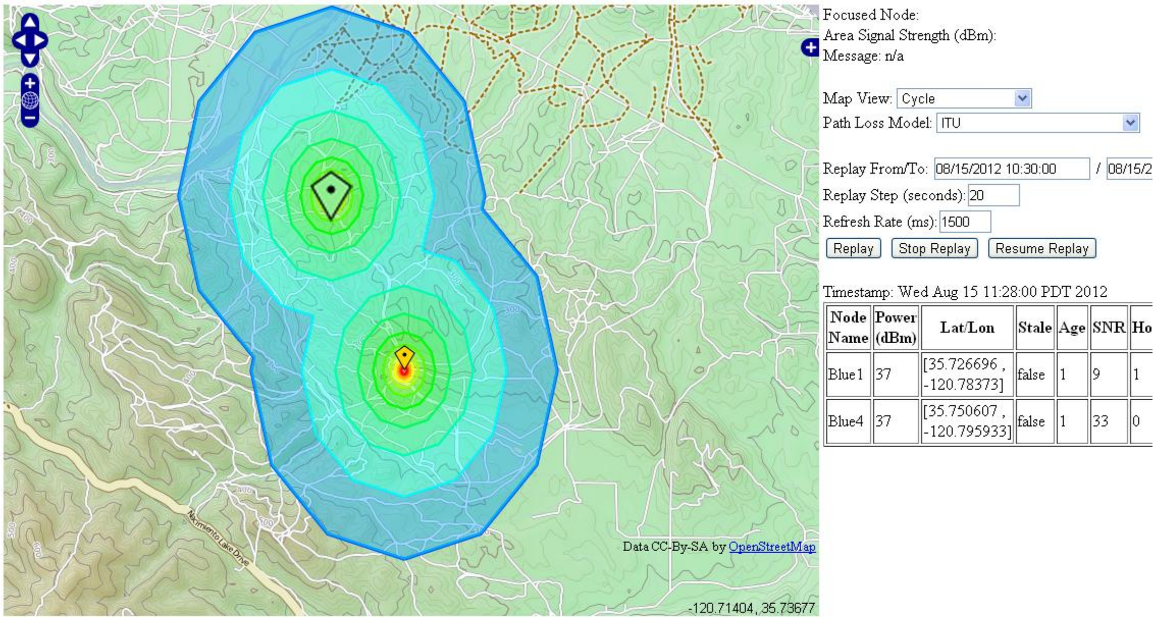

Figure 29. Heat Map Graphical User Interface Intuitively Displaying SNR As An Indicator of Network Quality (From Bourakov 2012)

V. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE WORK

The goal of this thesis is to describe a framework for a network management system that supports a robust self-management capability in MANETs. The motivation comes from developing Marine Corps tactical operations and command and control concepts. The major underlying concept for this research is an agent-based, policy-enabled network management framework for autonomic networks.

This research began by outlining the operating space defined by the Marine Corps' EMO/ECO concept, and how MANET systems are able to support tactical operations across a distributed and adaptive command and control force employment model. To maximize the capability of a network across these distributed and adaptive operations, planners must employ likewise-distributed and adaptive communications architectures. In this ubiquitous networking concept, the strength of the network lies with the nodes that comprise the physical edge of the network, implying the need that every entity on the battlefield represents a node on the network. Network management should then begin at the lowest maneuver elements to facilitate coordination of decentralized operations.

Such a bottom-up, distributed command and control structure serves as the foundation for an autonomic network framework that serves to evolve the network as a much more integral and active participant in the tactical environment. Therefore, every node must possess some self-contained autonomic management capability to distribute network management activities down to the individual node. The nature of this framework revolves around the knowledge element that serves as the hub from which an agent's autonomic decision-making cycle revolves. Critical elements of this proposed framework are a mobile agent (as an instance of the 8th layer hypernode concept described in Bordetsky and Hayes-Roth 2009), PBNM architecture, and a knowledge base supported CBR decision-making cycle. These three elements work together to form the root of the self-contained adaptive reasoning characteristic of autonomic networks.

A. CONCLUSIONS

Autonomic networks represent the ideal end state for the MCWL NGC2 conceptual NMS. While attaining this end state is beyond current capabilities of MANET platforms such as the TW-230 and existing C2 NMS programs, this research has identified how to build upon these existing systems towards attaining a true autonomic network. As a first step, this thesis examined the frameworks described by ADMA, DRAMA, and other research on policy-based network management and extended them to include an agent-based predictive/adaptive reasoning component.

Autonomic network management system begins with an agent-based framework. The agent represents a logical instance of a node and facilitates the employment of all the elements of autonomic network entities: contextual awareness, policy decisions, and policy execution. The ADMA specification, as an existing implementation of the basic 8th layer hypernode concept, provides a sufficient starting point to define the agents themselves. ADMA provides a solid framework for contextual processing, internal policy storage and analysis, and mechanisms for policy enforcement. These elements combined, comprise the agent system for every node and support the higher-level predictive/adaptive capabilities characteristic of autonomous networks.

Since these predictive/adaptive capabilities are the key enabling characteristic of autonomic networks, they should serve as the desired end state in evolving our current C2 capabilities. Building upon an agent framework to house this capability within every node, the broader framework for autonomic networks next requires a robust policy-enabled network management system. The DRAMA architectural framework provides an excellent PBNM system upon which to build. As a PBNM, DRAMA has many essential elements for defining, storing, distributing, and enforcing policy across a MANET. This policy-enabled management system is crucial for emulating the mission-type orders paradigm that must exist in a MANET supporting tactical operations. However, DRAMA does not include mechanisms for combining policy with context-awareness and knowledge derived some self-awareness within a hypernode. To extend this functionality to the existing DRAMA architecture, this research proposes inclusion of a knowledge base element to the policy elements that reside within the DRAMA framework.

Everything in the autonomic decision-making cycle revolves around the knowledge element; therefore, defining this element must be the first step towards defining a PBNM that ties network management activities with combat planning and execution. Hadjiantonis and Pavlou's (2009) DPR framework clearly describes how a knowledge base combines contextual awareness and policy actions to towards maximizing network quality and availability. However, the framework omits mechanisms to evaluate and recommend policy actions and control for possible policy conflict. Inclusion of CBR mechanisms within the policy control and execution phases of the autonomic cycle is critical in this respect. Since CBR employs the knowledge gained from experiences of the network to evaluate and recommend actions, CBR intuitively tends towards those crucial predictive and adaptive characteristics of autonomic networks.

A knowledge base, therefore, represents the collective memory of every node in the network, from which past experiences serve to support a competent decision-making cycle. This approach combines past policy events with current contextual inputs to make rapid policy execution decisions that are much less computationally intensive than other proposed approaches such as multivariate calculations of Pareto boundaries (Bordetsky and Hayes-Roth 2009). This reliance on experiences also supports reuse of the knowledge base for employment of a network in a new AOR. For example, an outbound unit in Afghanistan can provide a knowledge base to the incoming unit to load into their own NGC2 system, imparting all the learned experiences from the outbound unit's network.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

While the scope of this thesis described an agent-based, policy-enabled, autonomic command and control system framework, the mechanisms themselves that enable this capability are yet to be developed. Further research should work towards combining those separate, but complimentary mechanisms.

A major underlying element of any autonomic system is an effective policy creation, distribution, and management mechanism. While the DRAMA framework and work by Hadjiantonis and Pavlou (2009) provide the general outline for what a PBNM needs to do, they do little in terms of the human interface aspect. Further work should focus on development of human interfaces for designing policies, managing policy interactions across a network, and displaying those policy interactions in an intuitive way. A GUI of this type should be designed to allow a communications planner to construct policies for his or her network and facilitate the distribution and management of those policies.

Concurrent with developing intuitive GUIs for policy creation and dissemination, future research should address the need for similar mechanisms when interfacing with a system's knowledge base. Development of this interface should include development of knowledge base parameters and mechanisms to construct condition/action couplings and to link those couplings with policy enforcement mechanisms.

This thesis provides the framework needed to transform the Marine Corps' C2 concepts and capabilities by evolving tactical network management towards a capability that reflects a symbiosis between the operation's assets, the human elements, and the networks. Further research into the underlying principles contained within this framework can assist in the development of a command and control paradigm that compliments and enhances the Marine Corps' combat doctrine.

LIST OF REFERENCES

Aamodt, Agnar, and Enric Plaza. 1994. “Case-Based Reasoning□: Foundational Issues , Methodological Variations , and System Approaches.” *AI Communications* 7 (1): 39–59. doi:10.1.1.56.4481.

Allen, Tristan. 2012. “JIFX-12-4 Request For Information.” http://www.nps.edu/Academics/Schools/GSOIS/Departments/IS/Research/FX/JIFX/JIFX.html.

Ayari, Mouna, Zeinab Movahedi, Guy Pujolle, and Farouk Kamoun. 2009. “ADMA: Autonomous Decentralized Management Architecture for MANETs.” In *Proceedings of the 2009 International Conference on Wireless Communications and Mobile Computing Connecting the World Wirelessly - IWCMC ’09*, 132. New York, New York, USA: ACM Press. doi:10.1145/1582379.1582409.

Bordetsky, Alex. 2012. *Networking and Interagency Collaboration on Small Craft Maritime-Sourced Nuclear Radiological Threat Detection and Interdiction*. Monterey, Ca.

Bordetsky, Alex, Daniel Dolk, and George Zolla. 2004. *Application MIBs for Network Operation Centers Collaborative Management*.

Bordetsky, Alex, and Rick Hayes-Roth. 2009. “Hyper-Nodes for Emerging Command and Control Networks□: The 8th Layer.” In *International Command and Control Research and Technology Symposium*.

Bourakov, Eugene. 2012. “Graphical User Interface for Mobile Ad Hoc Networks”. Monterey, Ca.

Burbank, Jack L, Philip F Chimento, Brian K Haberman, and William T Kasch. 2006. “Key Challenges of Military Tactical Networking and the Elusive Promise of MANET Technology.” *IEEE Communications Magazine* 44 (11) (November): 39–45. doi:10.1109/COM-M.2006.248156..

Cho, Sungsoon. 2009. “Adaptive Management Schemes for Mobile Ad Hoc Networks.” doi:2027.42/63719.

Cho, Younchol, Jeffrey S. Smith, Alice E Smith, and Ieee Member. 2010. “Optimizing Tactical Military MANETs with a Specialized PSO.” In *IEEE Congress on Evolutionary Computation*, 1–6. IEEE. doi:10.1109/CEC.2010.5586275.

Conway, James (United States Marine Corps). 2008. "A Concept for Enhanced Company Operations."

El brak, Said, Mohammed Bouhorma, Anouar Boudhir, and Anouar A. Boudhir. 2011. "Network Management Architecture Approaches Designed for Mobile Ad Hoc Networks." *International Journal of Computer Applications* 15 (6) (February 28): 14–18. doi:10.5120/1954-2614.

Flynn, G.J. 2010. *Marine Corps Operating Concepts*. United States Marine Corps, Quantico, VA.

Ganek, a. G., and T. a. Corbi. 2003. "The Dawning of the Autonomic Computing Era." *IBM Systems Journal* 42 (1): 5–18. doi:10.1147/sj.421.0005.

Gateau, James. 2007. "Extending Simple Network Management Protocol (SNMP) Beyond Network Management." *Information Sciences*. Naval Postgraduate School.

Hadjiantonis, Antonis M. 2012. "Autonomic Management of Mobile and Wireless Networks." *Lecture Notes in Computer Science* 7216/2012: 199–208. doi:10.1007/978-3-642-30382-1_25.

Hadjiantonis, Antonis M, and George Pavlou. 2009. "Policy-Based Self-Management in Wireless Networks." In *Context-Aware Computing and Self-Managing Systems*, ed. Waltenegus Dargie, 3:201–264. Chapman and Hall/CRC. doi:10.1201/9781420077728.ch7.

Halford, Thomas R, and Keith M. Chugg. 2010. "Barrage Relay Networks." In *2010 Information Theory and Applications Workshop (ITA)*, 1–8. IEEE. doi:10.1109/ITA.2010.5454129.

Hayes-Roth, Frederick. 2006. "Model-Based Communication Networks and VIRT: Orders of Magnitude Better for Information Superiority." In *MILCOM 2006*, 1–7. IEEE. doi:10.1109/MILCOM.2006.302354.

Hayes-Roth, Frederick, and Curtis Blais. 2008. "A Rich Semantic Model of Track as a Foundation for Sharing Beliefs Regarding Dynamic Objects and Events." *Intelligent Decision Technologies* 2 (1): 53–72.

Hunjet, Robert A, Andrew Coyle, and Matthew Sorell. 2010. "Enhancing Mobile Adhoc Networks Through Node Placement and Topology Control." In *2010 7th International Symposium on Wireless Communication Systems*, 536–540. IEEE. doi:10.1109/ISWCS.2010.5624347.

Iskander, Adel F, and Akmal A Younis. 2008. “A Proactive Management Algorithm for Self-healing Mobile Ad Hoc Networks.” *International Journal of Network Management* 18 (3) (May): 229–250. doi:10.1002/nem.654.

Kephart, J.O., and D.M. Chess. 2003. “The Vision of Autonomic Computing.” *Computer* 36 (1) (January): 41–50. doi:10.1109/MC.2003.1160055.

Konak, Abdullah, Orhan Dengiz, and Alice E Smith. 2011. “Improving Network Connectivity in Ad Hoc Networks Using Particle Swarm Optimization and Agents.” In *Wireless Network Design: Optimization Models and Solution Procedures*, ed. Jeff Kennington, Eli Olinick, and Dinesh Rajan, 158:247–267. New York, NY: Springer New York. doi:10.1007/978-1-4419-6111-2_11.

Matkins, Joseph. 2010. *MCWL C4-LOE 3.2 Tech Div Executive Summary*.

Mills, Richard P (Combat Development and Integration/USMC). 2012. *2012 U.S. Marine Corps S&T Strategic Plan*.

Mishra, Atul, and A.K K Sharma. 2010. “Role of Agents in Distributed Network Management□: A Review.” *International Journal of Advancements in Technology* 1 (2): 284–295.

Ntuen, Celestine A, and Gwang M Kim. 2011. “An Agent-based Model Simulation of Multiple Collaborating Mobile Ad Hoc Networks (MANET).” In *16th International Command & Control Research and Technology Symposium Collective C2 in Multinational Civil-Military Operation*, 51.

Oros, Carl. 2007. *Experimental Design and Testing of a Hyper- Node Enabled Distributed Operations Tactical Command and Control Network*.

Potier, Paul, and Lijun Qian. 2011. “Network Management of Cognitive Radio Ad Hoc Networks.” In *Proceedings of the 4th International Conference on Cognitive Radio and Advanced Spectrum Management - CogART ’11*, 1–5. New York, New York, USA: ACM Press. doi:10.1145/2093256.2093294.

Puff, Chad J. 2011. “Network Management System for Tactical Mobile Ad Hoc Network Segments.” *Information Sciences*.

Sharvani, G S, and T M Rangaswamy. 2011. “Development of Swarm Intelligence Systems for MANETs.” *Int. J. on Recent Trends in Engineering & Technology* 05 (01): 163–165.

Vanderhorn, Nathan, Benjamin Haan, Marco Carvalho, and Carlos Perez. 2010. "Distributed Policy Learning for the Cognitive Network Management System." In *The 2010 Military Communications Conference*, 435–440.

Wolberg, Michelle, Ritu Chadha, Cho-Yu Jason Chiang, Kathleen Kurachik, Marcus Pang, and Gregory Hadynski. 2011. "Using an Adaptive Management Plane for Policy-based Network Management Traffic in MANETs." In *2011 - MILCOM 2011 Military Communications Conference*, 1133–1138. IEEE. doi:10.1109/MILCOM.2011.6127451.

.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Marine Corps Representative
   Naval Postgraduate School
   Monterey, California

4. Director, Training and Education, MCCDC, Code C46
   Quantico, Virginia

5. Director, Marine Corps Research Center, MCCDC, Code C40RC
   Quantico, Virginia

6. Marine Corps Tactical Systems Support Activity (Attn: Operations Officer)
   Camp Pendleton, California

7. D.C. Boger
   Naval Postgraduate School
   Monterey, California